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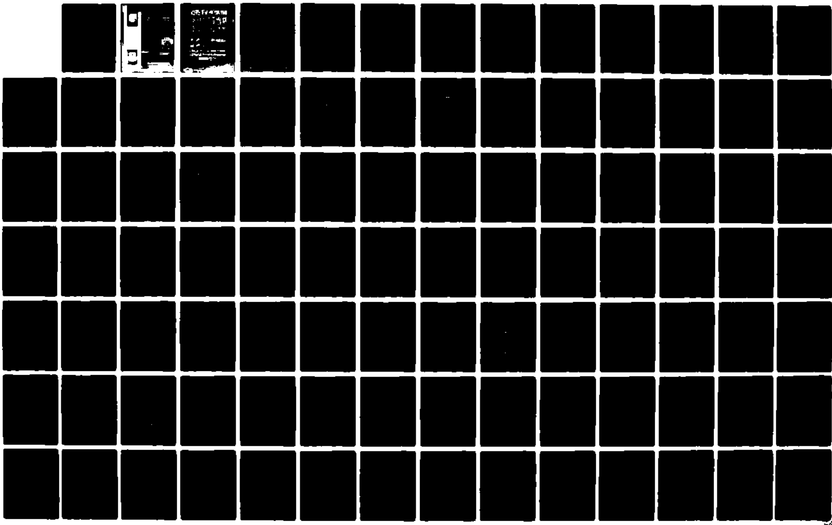

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This User Guide documents the Turbofan Engine Technology Evaluation System developed to fulfill one of the goals of a basic research project at the Frank J. Seiler Research Laboratory (Air Force Systems Command), a tenant organization located at the United States Air Force Academy in Colorado Springs, Colorado. The authors included two full-time researchers, Maj Arthur E. Fanning, and Capt Victor J. Villhard; two reserve officers, Capt William Dieterich and Maj C. Bruce Harmon; two college students who worked at the lab between semesters, Mr. Dwayne Davis and Mr. A. Scott Mediavilla; and an Air Force Academy graduate awaiting Pilot Training, 2Lt John W. Wood. It took us from Fall 1981 to Winter 1983 to completely write and document this system.

The User Guide is intended to be used as a supplement to the bulk of the system documentation included as extensive commenting of the FORTRAN source coding of the programs and subroutines that make up this system.

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The User Guide includes a description of the general layout of the system, the general approach used in calculating gas properties throughout the engine simulation model, the recommended limitations and suggested constraints of the system, how the performance calculated by TRBOFN, the engine simulation program in this system, compares to SMOTE, an accepted standard turbofan engine simulation program, and discussion of the general conventions followed in developing the system.

The Turbofan Engine Technology Evaluation System is intended to be a computer age "back-of-the-envelope" calculation tool for use in evaluating the relative payoffs of competing gas turbine engine technologies. The system consists of four programs:

SETUP - an interactive graphics program used to select and input design cycle parameters for the engine and the flight conditions at which performance is to be calculated;

TRBOFN - the turbofan engine performance simulation program;

ENCOM - an interactive engine sizing and comparison program that also allows selection of performance parameters for graphs and comparison of up to five engines' performance powering an airplane through an eleven leg fighter/ground attack mission. The bottom line output in this comparison is the minimum fraction of take-off gross weight that must be fuel for the airplane to complete the mission using each engine under consideration; and

GRAPH - an interactive graphics program for the creation of publication quality graphs of almost any calculated parameter versus any other.

Since the interactive graphics sections of the system make it so easy to use, and since it is such a versatile system, it is most useful in tasks related to turbofan engine design and performance analysis as well as in training new people unfamiliar with engine performance calculations or trends.

The interactive graphics sections of the above listed programs as originally written require use of Tektronix PLOT 10 Interactive Graphics Library and a Tektronix 4112 graphics terminal.

BLOCK 18 CONTINUED:

Interactive Computer Graphics
Turbofan Engine Technology Comparison
Turbofan Engine Performance Comparison

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LIST OF FIGURES

Page No.

How to Use this Guide:

1. Get a printout of the FORTRAN SOURCE or compiled versions of the programs and subroutines that make up this system.

2. This User's Guide is a SUPPLEMENT to the bulk of the system documentation included as extensive commenting of the program coding.

3. If you want to know about the GENERAL LAYOUT of the system, you can find that information conveniently either in this guide or by looking at the mainlines of the four programs that make up the system.

4. If you want to know about the recommended LIMITATIONS of this system, this document will answer those kinds of questions.

5. If you want to know WHY A COMPONENT WAS MODELLED THE WAY IT WAS, this document should answer those questions, too.

6. This guide also includes some discussion of the GENERAL CONVENTIONS we followed in developing this system.

7. You'll have to look at the PROGRAM PRINTOUTS to find the DETAILED APPROACH we used in modelling the engine components and performance.

Chapter 1

INTRODUCTION: What's It All About?

What is this system supposed to do?

This Turbofan Engine Technology Evaluation System is intended to be a computer age "back-of-the-envelope" calculation tool for use in evaluating the relative payoffs of competing gas turbine engine technologies. A system capable of performing all the tasks required to fit that description must be versatile and that's one thing this system is. To be useful, we thought the system should also be easy to use and understand. The page titled "How to Use this Guide" is intended to give you a head start toward using and understanding everything you want to know about this system.

Who wrote it?

This system was developed to fulfill one of the goals of a basic research project at the Frank J. Seiler Research Laboratory (Air Force Systems Command), a tenant organization located at the United States Air Force Academy in Colorado Springs, Colorado. The authors included two full-time researchers, Maj Arthur E. Fanning, and Capt Victor J. Villhard; two reserve officers, Capt William Dieterich and Capt C. Bruce Harmon; two college students who worked at the lab between semesters, Mr. Dwayne Davis and Mr. A. Scott Mediavilla; and an Air Force Academy graduate awaiting Pilot Training, 2Lt John W. Wood. It took us from Fall 1981 to Winter 1983 to completely write and document this system.

What programs make up the system?

SETUP: an interactive graphics program used to select and input design cycle parameters for the engine and the flight conditions at which performance is to be calculated.

TRBOFN: the turbofan engine performance simulation program

ENCOM: an interactive engine sizing and comparison program that also allows selection of performance parameters for graphs

GRAPH: an interactive graphics program for the creation of publication quality graphs of almost any calculated parameter versus any other.

Are these programs easy to understand and use?

All four programs in this system are modular. That is, they are made up of calls to many, many short, easy to understand subroutines. Each subroutine is completely internally documented and explained in the programming code. Most are also mentioned in this User Guide.

How might I use this system?

I hope you'll find this system useful in your tasks related to turbofan engine design and performance analysis as well as in training new people who might be unfamiliar with engine performance calculations or trends.

What's in this document that isn't in the programming code?

This User Guide describes:

- the general layout of the system; in other words, the picture that covers just a little more than the level that describes the purposes and workings of the main programs,

- limitations of the system models and suggested constraints,

- the general approach used in calculating gas properties throughout the engine simulation model, TRBOFN,

- why the engine components were modeled the way they were in TRBOFN,

- what output products you can get from this system,

- how the performance calculated by TRBOFN, the engine simulation program in this system, compares to SMOTE, an accepted standard turbofan engine simulation program.

GENERAL INFORMATION ON THE PROGRAMS:

SETUP is an interactive graphics program which allows the user to select and change engine design prameters and off-design flight conditions for TRBOFN to use in calculating engine performance. On each run of SETUP, you can design up to five engines to be run by TRBOFN. SETUP creates a data file that TRBOFN reads.

TRBOFN is a parametric engine simulation program capable of calculating performance trends for both mixed and separate flow engine designs. Gas properties are calculated by subroutines which reproduce the calculations Keenan, Chao and Kaye outline in their book, Gas Tables. TRBOFN has a control schedule built into it to simulate performance of the engine at throttled power settings. Calculated performance consists of temperatures, pressures, Mach numbers and gas properties at about 50 stations through the engine, engine thermodynamic efficiencies, thrust and specific fuel consumption.

ENCOM performs sizing and comparison functions on up to five engines whose performance was calculated by TRBOFN. It scales the physical size of each engine so that each can propel the same airplane through a set of up to five user-chosen maneuver conditions. For instance, you might want the airplane to be able to (1) sustain a 6g turn at Mach 0.9 at 20,000 ft altitude, (2) be able to produce a 1g acceleration at sea level for takeoff, (3) be able to dash at Mach 2.3 at 10,000 ft and (4) cruise at Mach 0.85 at 40,000 ft. ENCOM includes a drag polar for a fighter type airplane which can easily be modified to fit any airplane you want. It determines the thrust requirements for each of the maneuvers you specified from the drag parameters. It then scales the physical size of each of the engines to produce enough thrust at each flight condition to meet each maneuver requirement. Whichever maneuver required the largest size for each of the five engines is the "critical maneuver requirement" for that engine. The relative size information for each of the five engines is then stored and output. ENCOM can be used to determine the optimum engine cycle in terms of physical size for a given mission by specifying certain maneuver conditions and looking at the relative sizes of engines with a range of cycle parameters. But it even goes a step further by allowing the user to compare the relative performance of the engines flying through an eleven-leg mission. Using this section of the program, you can optimize the engine based on TSFC or thrust margins available or any other criterion you'd like to use. ENCOM also collects parameters from the TRBOFN-generated engine performance data files for plotting so you can examine trends and determine optimum cycle designs using graphic displays to present complex trends and relations in an easily understandable and readily usable form.

GRAPH is the program that allows you to plot performance trends, etc. It is an interactive graphing program which uses Tektronix' Interactive Graphics Library (IGL). The graphing program also depends on features unique to Tektronix 411X series terminals. GRAPH could easily be modified to work on almost any other Tektronix terminal. It would probably be less versatile but IGL does include subroutines to allow other terminals to emulate many ot the 411X features. Obviously, if you don't have access to IGL and you do have access to another graphics package you could write a program using it to replace GRAPH. The only constraint is that it would have to be written to read data files of the form ENCOM writes.

INFORMATION ON OUTPUT PRODUCTS:

SETUP: You can see a sample data file produced by SETUP at the end of Chapter 2. It contains all the information TRBOFN needs to design and calculate perormance for up to five engines at the design flight condition and up to 19 off-design flight conditions. SETUP also creates an output file used by ENCOM for input of maneuver conditions for sizing and comparison.

TRBOFN: The output file from TRBOFN includes design and off-design information for the engine simulated with information about internal pressures, temperatures, Mach numbers and fuel-to-air ratios at about 50 stations inside the engine for each operating condition. It also includes thrust expressed in two ways,thrust specific fuel consumption and engine efficiencies at all user-input operating cooditions. Thrust is expressed both as a non-dimensional quantity proportional to the physical size of the engine and a thrust per total engine airflow. These expressions of thrust are used in the sizing process performed in ENCOM. The non-dimensional thrust expression is net thrust per sea level static pressure per flow area at the first stage turbine vane choke point ($F_n/(P_{sl}\ A_{41})$). All station areas in the design process are calculated as fractions or multiples of this area, A_{41}. Thus, the non-dimensionalized thrust is directly proportional to engine size. In other words, to get a thrust of 20,000 lbs from an engine with a non-dimensional thrust of 20.0 would require the product ($P_{sl}\ A_{41}$) to be 1,000 and since P_{sl} = 14.69 psi, A_{41} would be (1,000/14.69) sq in or 68.07 sq in or 0.4727 sq ft. All the other station flow areas are calculated as fractions or multiples of A_{41} so it would then be trivial to calculate any other engine station flow area.

ENCOM: Two kinds of output files are created by ENCOM: one kind contains x-y pairs for plotting with GRAPH, the other is a Mission Performance file. The file for plotting is in a simple form. The first line in the file contains the number of curves to be drawn on the graph, NLINES. The rest of the file is made up of NLINES groups of numbers, each in the same form. Each group consists of the number of x-y pairs that are to be connected to make the line, NPTS, followed by that many x-y pairs, one on each line in the file. GRAPH will plot the numbers in any file in this form. The mission performance output file contains performance information on each of up to five engines for each of the eleven legs of the mission. It includes such information as thrust required on each leg, time to complete the leg, distance travelled, fuel used on each leg as fraction of take-off gross weight of the aircraft and wing loading used on each leg based on remaining fuel fraction and take-off wing loading. The bottom line output in this file is the minimum fraction of take-off gross weight that must be fuel for the airplane to complete the mission using each engine under consideration.

GRAPH: Publication quality plots with user-selected labels and axis scaling can be made with GRAPH. Many examples of outputs from GRAPH are included in this document, especially in the Appendix.

Chapter 2.

SETUP: Interactive Graphics Design Input Program

INTRODUCTION:

SETUP is the interactive graphics program used in this system to input and change engine design and off-design information which is used by TRBOFN to calculate the performance of the engine(s) you design at the flight conditions you request.

SETUP is easy to run since almost all the instruction you need to run it appears on the screen. This chapter of the User's Guide is intended to show you each screen you would see running SETUP on the terminal for which it was written, the Tektronix 4112. If you don't have access to a 4112 terminal, you may have to modify SETUP before it will work on your terminals. SETUP is written using Tektronix' Interactive Graphics Library (IGL). If you do not have access to IGL but you do have access to another graphics library, you can write a SETUP program of your own using your graphics library to do the things described in this chapter.

When you run SETUP, the first thing you see is an animated engine building the title screen. When the animated engine is finsihed flying across the screen it looks like Figure 1 below.

TURBINE ENGINE

TECHNOLOGY/PERFORMANCE

EVALUATION SYSTEM

F.J. SEILER RESEARCH LABORATORY 1983

Figure 1. Title Screen

After a pause of a few seconds, the screen goes blank and the next screen appears.

The first input parameter you get to choose is the number of engines you'd like to design on this run through SETUP. Enter a number from 1 to 5 and press return to get to the next screen.

ENTER THE NUMBER OF ENGINES FOR WHICH YOU

WOULD LIKE TO ENTER DESIGN PARAMETERS.

ALL DESIGN INFORMATION WILL BE WRITTEN TO THE SAME

DATA FILE TO BE READ BY THE PROGRAM TRBOFN

NUMBER OF ENGINES:

2. Selecting Number of Engines

Once you enter the number of engines you want to design, the program announces that you are going to be selecting design parameters for engine number 1 as follows:

ENGINE DESIGN PARAMETER SELECTION

FOR ENGINE NUMBER 1

IN THIS SECTION OF THE PROGRAM YOU WILL BE ALLOWED

TO SELECT AND CHANGE ALL THE PARAMETERS NECESSARY

FOR THE PROGRAM TRBOFN TO DESIGN AND CALCULATE

DESIGN AND THROTTLED PERFORMANCE FOR THE ENGINE

Figure 3. Announcement Page for Engine Number 1

TRBOFN is capable of simulating performance of both mixed and separate flow engine designs so the next thing you get to specify for the engine you're designing is which type it is.

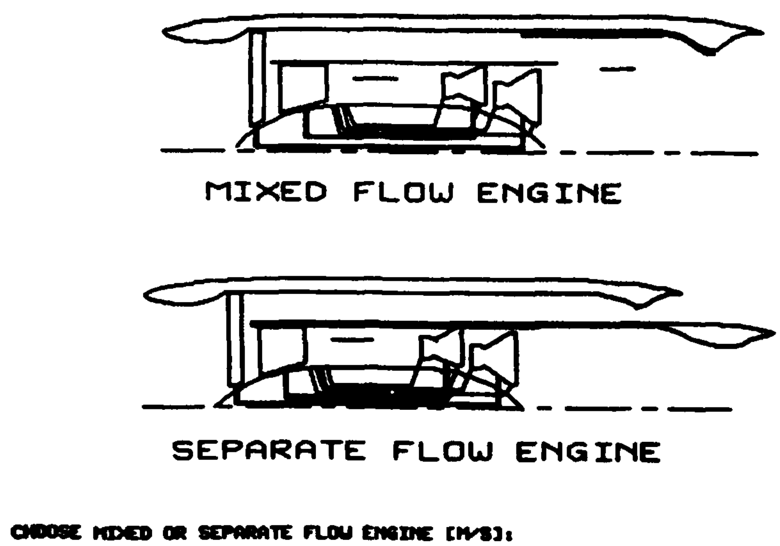


Figure 4. Mixed or Separate Flow Design

The next screen to appear is the first design parameter menu. The next two figures show how highlighting works. All the parameters on this first menu refer to the compression section of the engine so the compression section of the engine drawn in the top half of the screen blinks on and off.

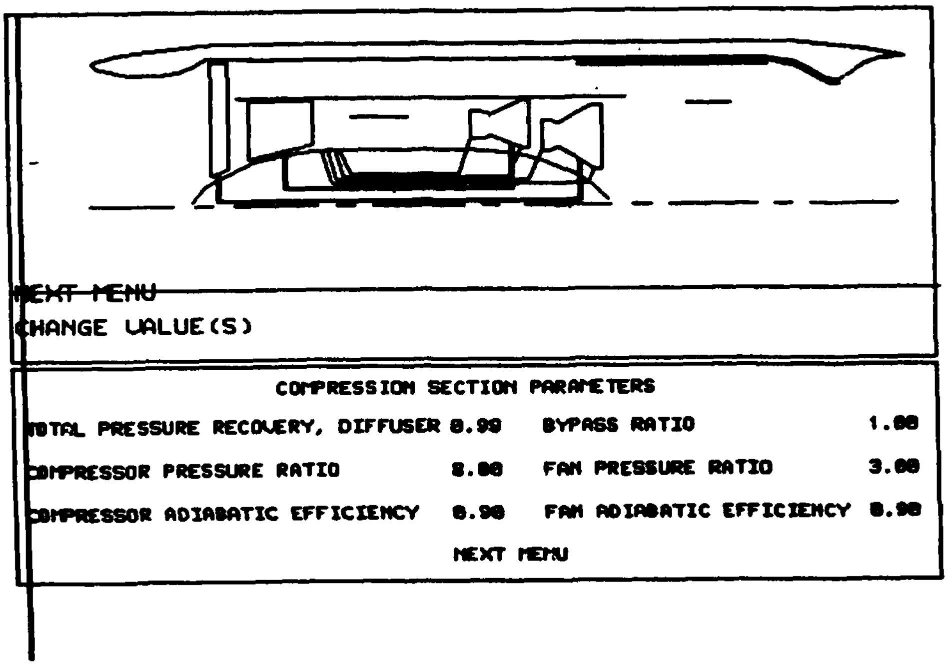


Figure 5a. Compression Section Highlighting

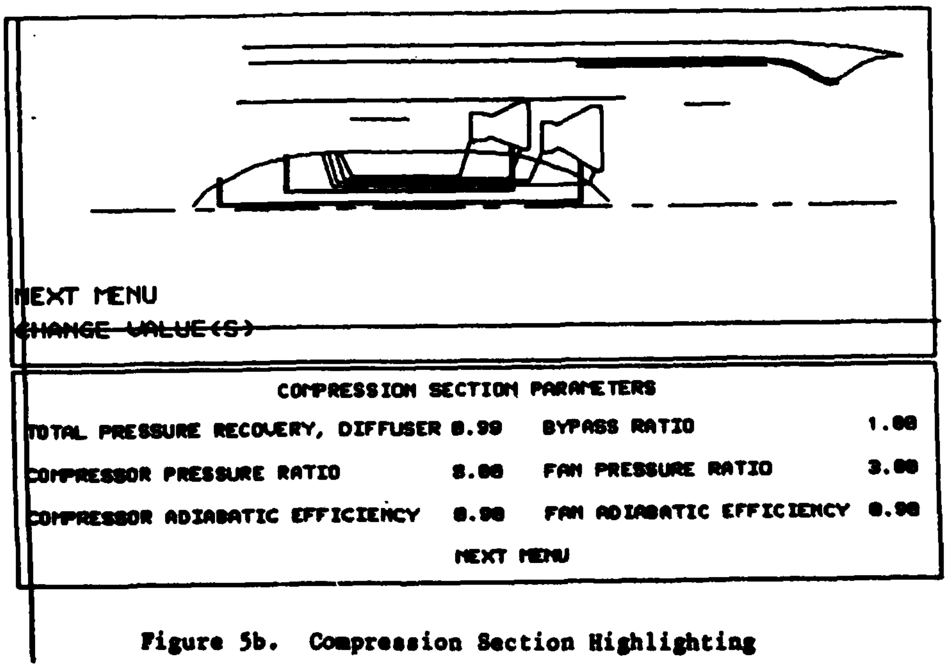


Figure 5b. Compression Section Highlighting

To change parameters in the menu, move the crosshair cursor onto "CHANGE VALUE(S)" and press any alphanumeric key or **RETURN** (Figure 5b). The cursor jumps into the menu section of the screen and is placed on "NEXT MENU" at the bottom of the box as shown in Figure 6.

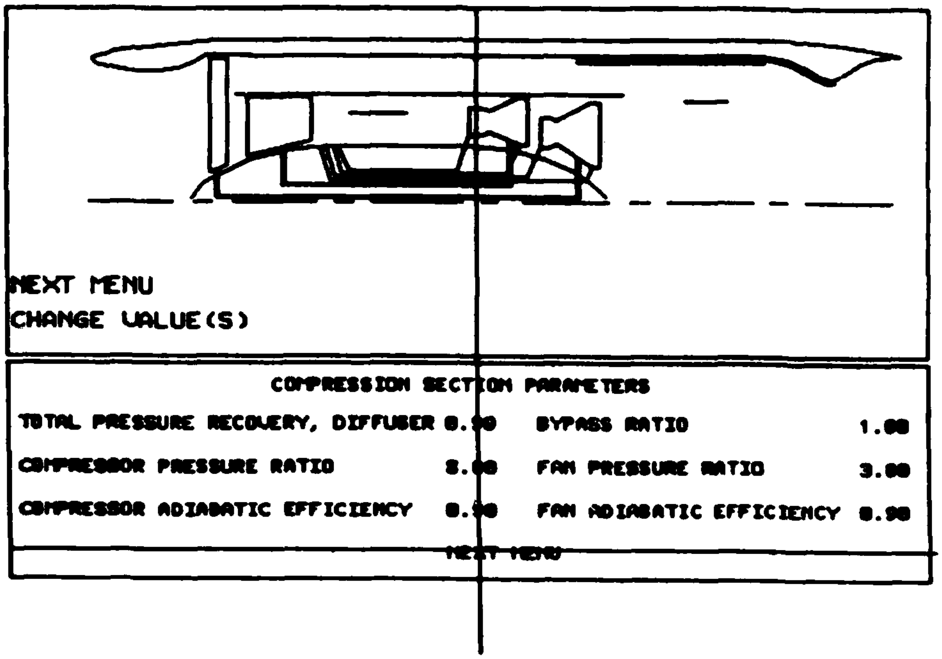


Figure 6. Menu 1: Compression Section Parameters

To change a parameter in this menu, move the crosshair cursor onto the value you want to change and press any key.

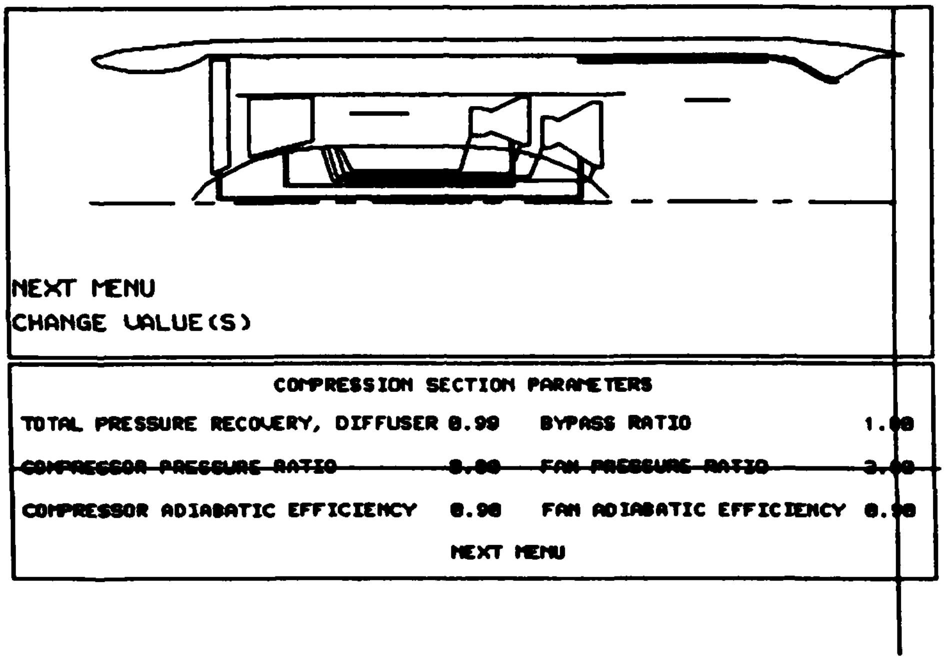


Figure 7. Select a Parameter to Change

When you press the key, the value the cursor was on disappears from the menu and a prompt for the parameter you chose appears at the bottom of the screen. The prompt string you see at the bottom of the screen is the name of the parameter used in the program SETUP and in the engine simulation program, TRBOFN.

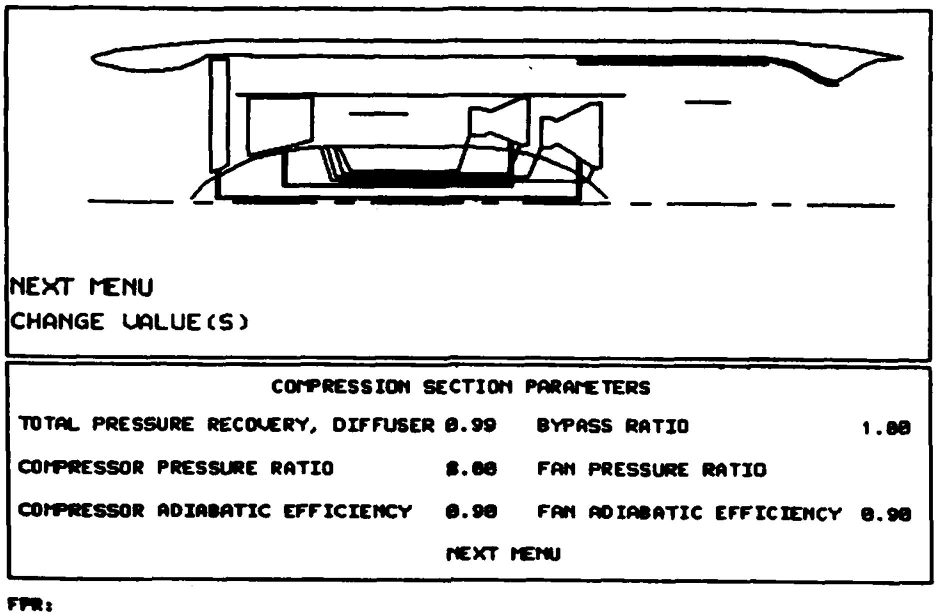


Figure 8. Prompting for a New Value

At this point, enter the new value you want the parameter to have (in this example, 2.7) and press RETURN. The new value will reappear in the place where the old one was and the cursor will reappear on "NEXT MENU". If you want to change any other parameters, move the cursor onto the value you want to change and follow the same procedure. If all the values on the menu are satisfactory, simply press any key while the cursor is on the "NEXT MENU" selection in the menu and the next menu will appear.

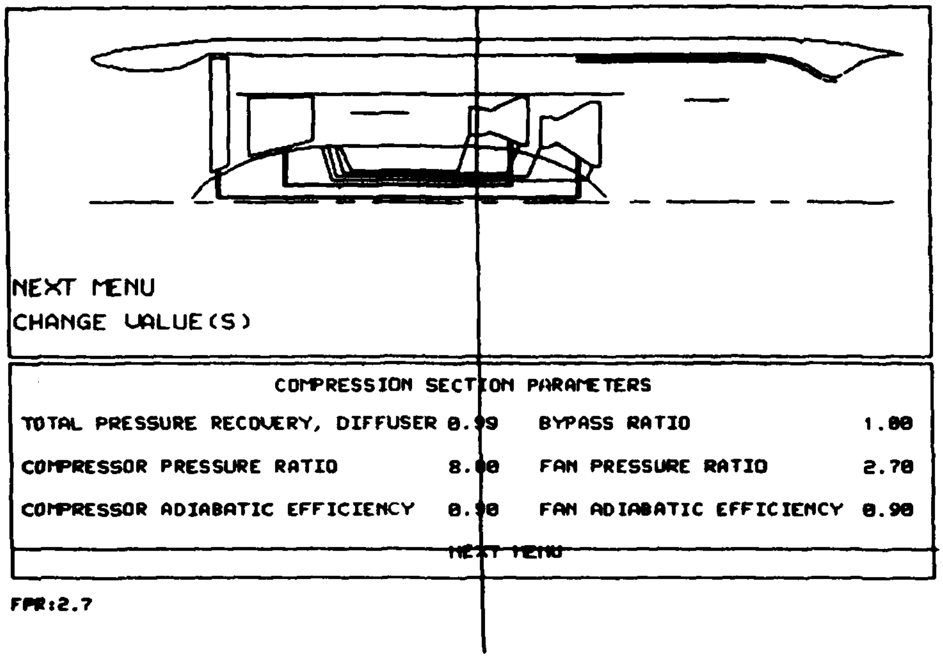


Figure 9. New Value in Place of Old One

The second menu includes all the parameters the program TRBOFN needs to calculate the effects of using an alternate fuel to run the engine. The parameters that appear by default (shown in Fig 10) are for JP-4. To change any or all of them, follow the same procedure as described above for changing the fan pressure ratio. The burner splitter plate is highlighted (i.e., blinks on and off) on this screen.

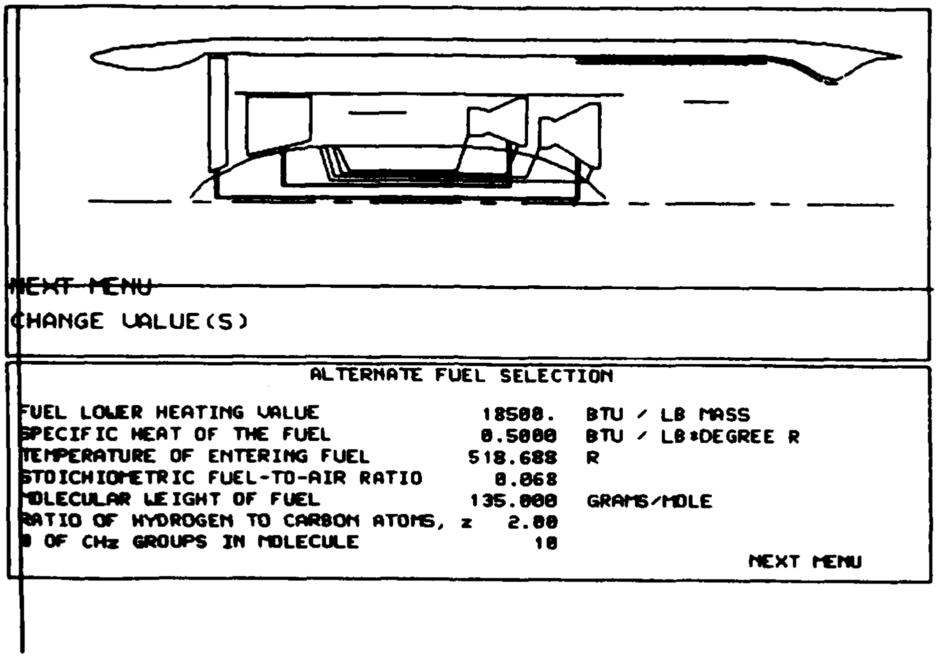


Figure 10. Menu 2: Alternate Fuel Selection

When you select either "NEXT MENU" this screen appears. TRBOFN needs several internal Mach numbers at design to calculate flow areas in the engine for use in off-design performance and balancing calculations. The third menu allows you to change four of the necessary design Mach numbers. The station designator lines are highlighted on this screen.

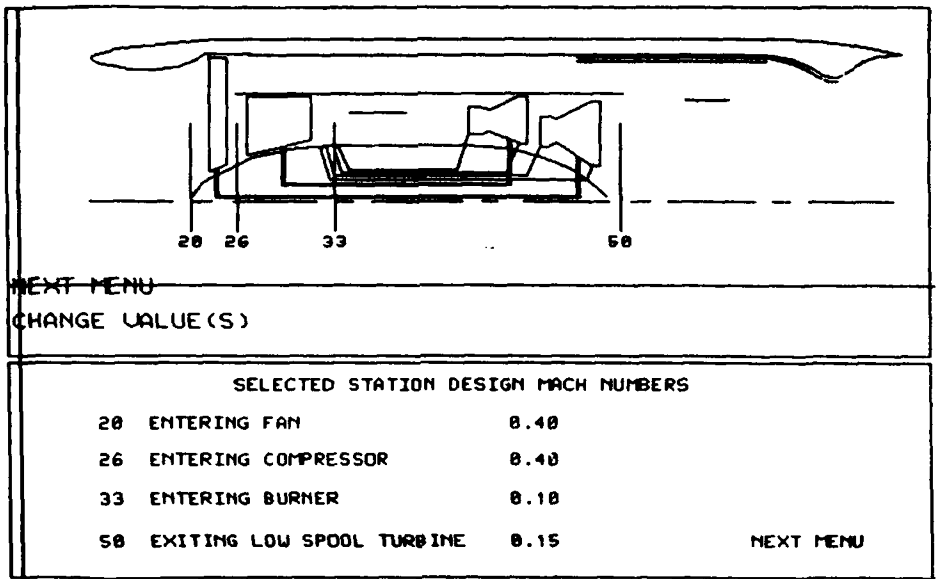


Figure 11. Menu 3: Internal Flow Mach Numbers

The next menu allows you to select the control scheme to be used to determine the intermediate power setting for the engine you're designing when it runs at off-design flight conditions. You can choose to have TRBOFN consider either of two temperatures as one of the possible control parameters while searching for off-design intermediate power settings: the turbine inlet gas temperature or the first stage vane metal temperature. If you choose to have it check gas temperature, this is the menu where you get to set its limiting value. You can set the maximum allowable metal temperature on a different menu.

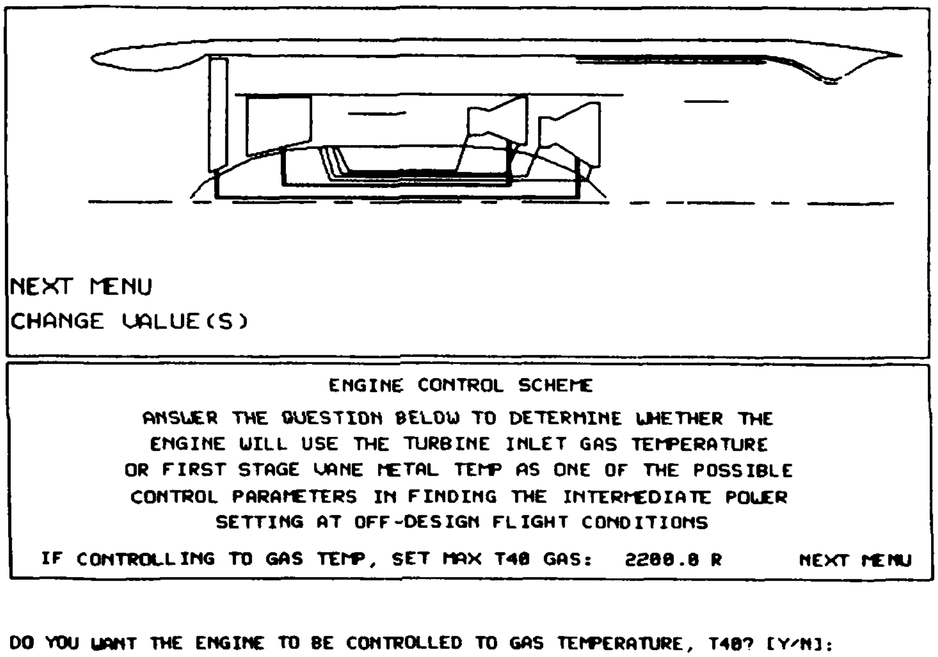


Figure 12. Menu 4: Control Parameter Selection

When you answer the question "yes", the cursor appears in the menu block on "NEXT MENU". At this point you can change the value of the gas temperature to be used as a control parameter from 2220 R to whatever you like. Place the cursor on "NEXT MENU" and hit any key to go on to the next menu.

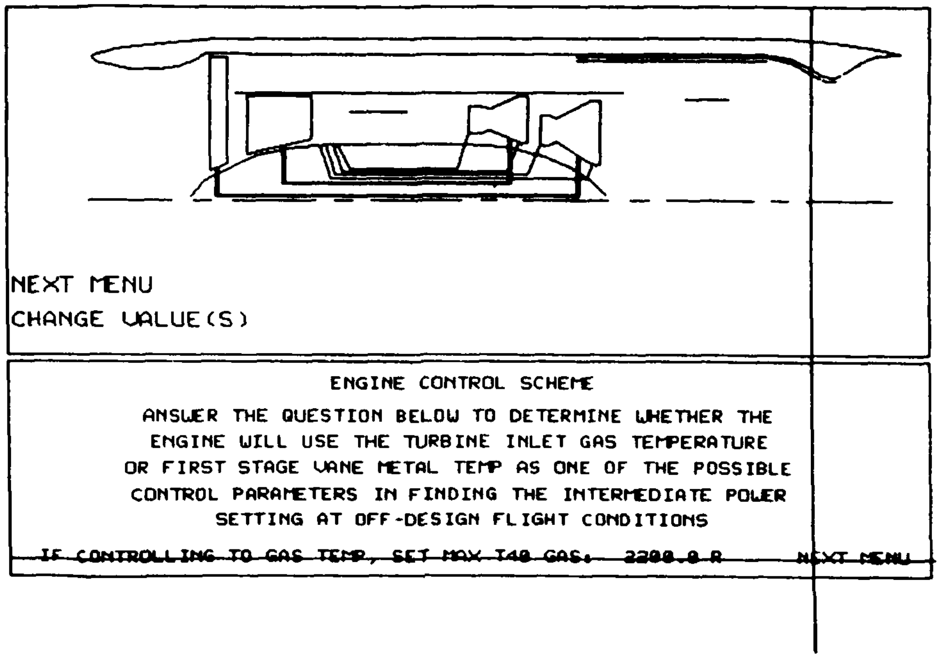


Figure 13. Menu 5: Setting the Gas Temperature for Control

On the next menu you get to set the adibatic efficiency of the two turbines in the engine. Change them in the same way as any other menu parameter.

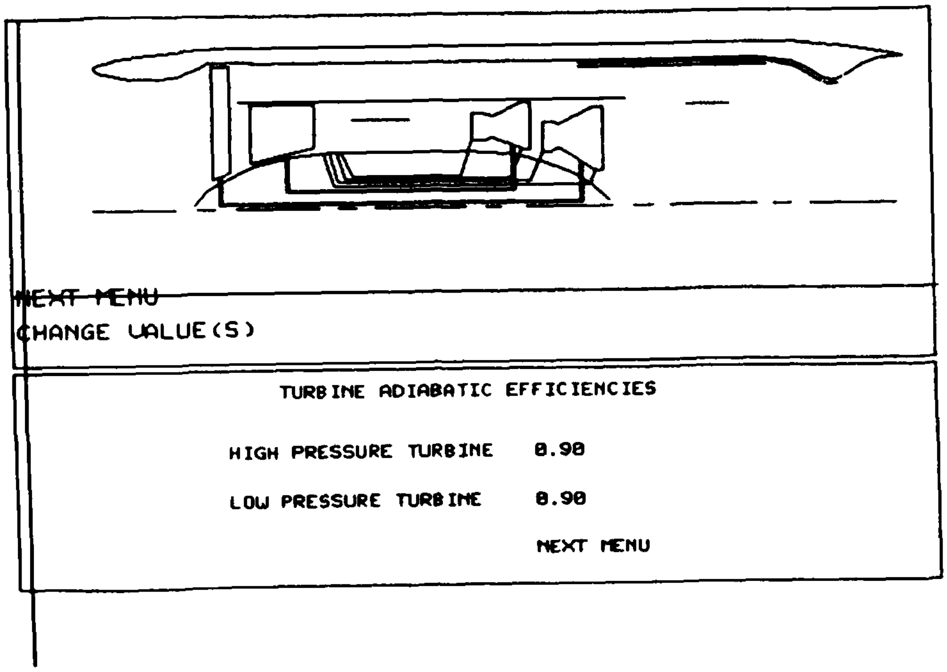


Figure 14. Menu 6: Turbine Adiabatic Efficiencies

Next, you must answer another question. This time you must decide whether you want to set any turbine cooling parameters. For the purposes of showing as many of the program screens as possible, let's answer the question "yes" and see all the possible turbine cooling parameters you can set.

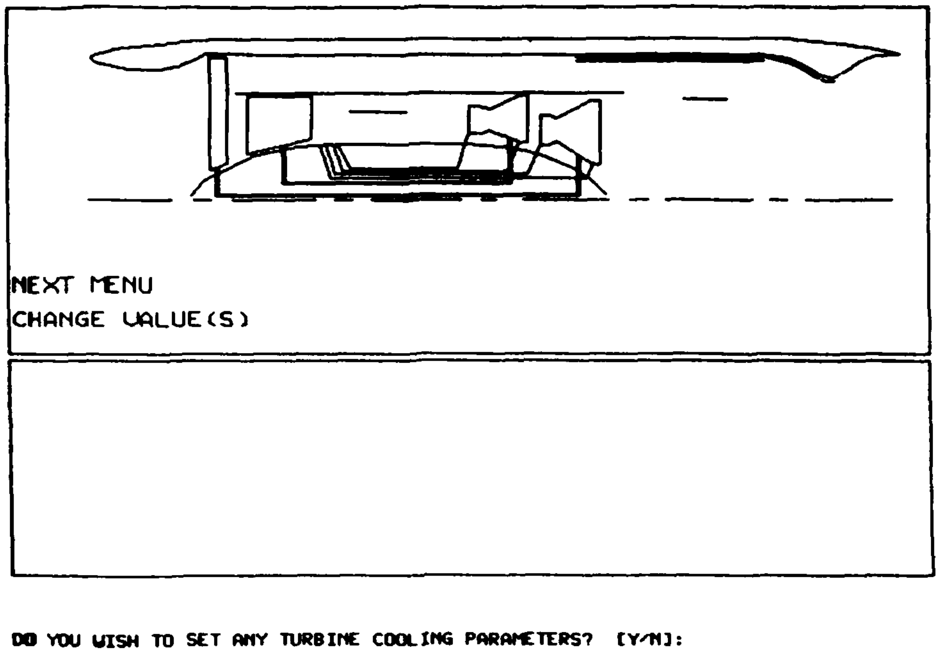
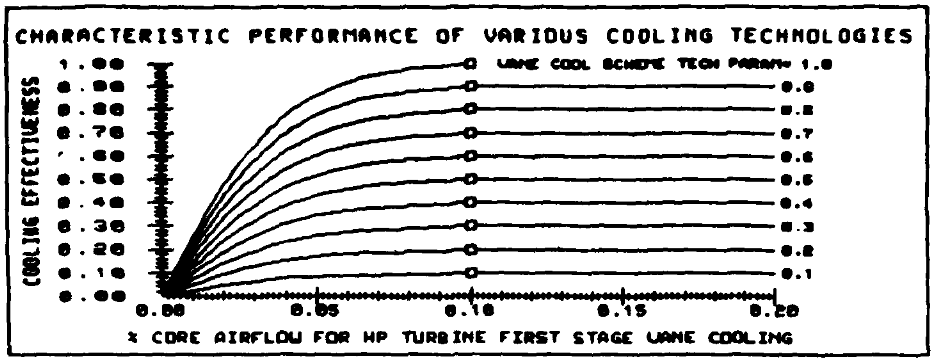


Figure 15. Question on Setting Turbine Cooling Parameters

The instructions on how to select a high pressure turbine vane cooling scheme technology level are self-explanatory. Read the text at the bottom of each of the following screens. PMCTVH stands for Percent core Massflow for Cooling the Turbine Vanes of the High pressure turbine.

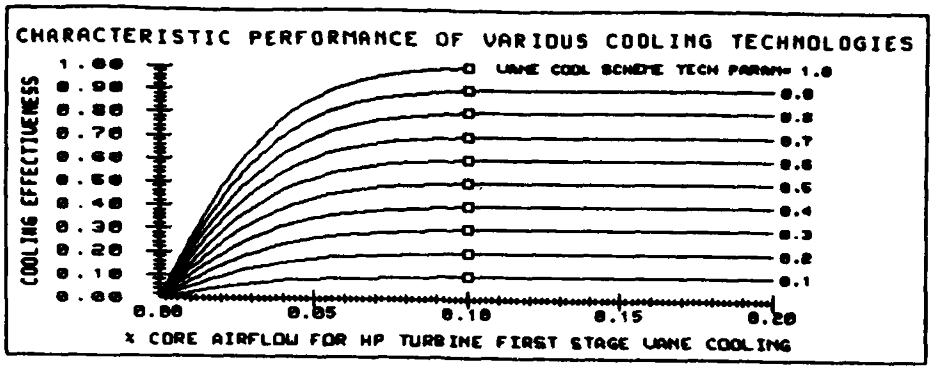


SPECIFYING THE TECHNOLOGY LEVEL OF THE HP TURBINE VANE COOLING SCHEME

THIS SELECTION IS MADE FROM A SERIES OF CHARACTERISTICALLY SHAPED CURVES REPRESENTING TEN VALUES OF THE COOLING SCHEME TECHNOLOGY PARAMETER. THE CHARACTERISTIC SHAPE IS SIMILAR TO A HYPERBOLIC TANGENT CURVE. THE COOLING SCHEME TECHNOLOGY PARAMETER IS THE COOLING EFFECTIVENESS OF THE SCHEME USING 10% OF THE TOTAL CORE AIRFLOW FOR VANE COOLING. SELECT A COOLING SCHEME TECHNOLOGY BY PICKING A POINT WHERE PMCTVH=10% AND THE VALUE OF THE COOLING EFFECTIVENESS IS THE VALUE YOU WANT TO USE FOR THE TECHNOLOGY PARAMETER.

NEED ANY MORE INSTRUCTIONS? [Y/N]:

Figure 16a. Instructions for Selecting a High Pressure Turbine Vane Cooling Scheme Technology Level

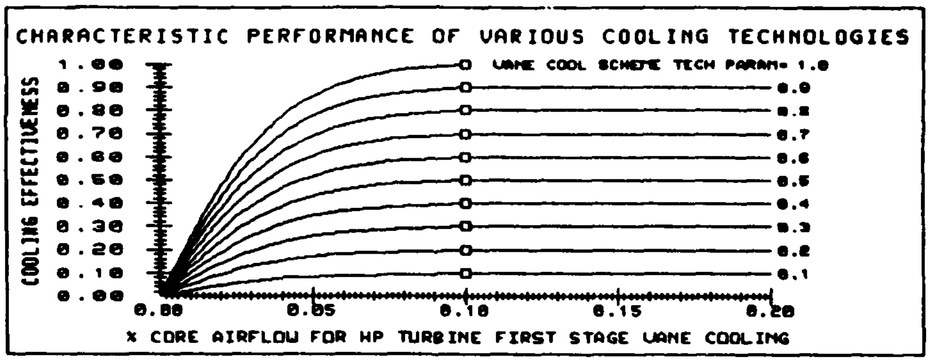


"TRBOFN" USES THE TECHNOLOGY LEVEL INFORMATION TO CALCULATE THE COOLING EFFECTIVENESS AND % CORE FLOW REQUIRED TO COOL THE FIRST STAGE VANE METAL TO ITS SPECIFIED MAXIMUM ALLOWABLE TEMPERATURE WHILE EXPOSED TO THE STOICHIOMETRIC FLAME TEMPERATURE IF THAT IS POSSIBLE WITH THE SELECTED COOLING TECHNOLOGY.

IN OTHER WORDS, THE COOLING SCHEME IS SET UP FOR THE "HOT SPOT" ON THE VANE METAL TO BE AT THE MAXIMUM ALLOWABLE METAL TEMPERATURE WHILE THE REST OF THE VANE IS COOLER.

HIT RETURN TO GO ON

Figure 16b. HP Turbine Vane Cooling Scheme Technology Level

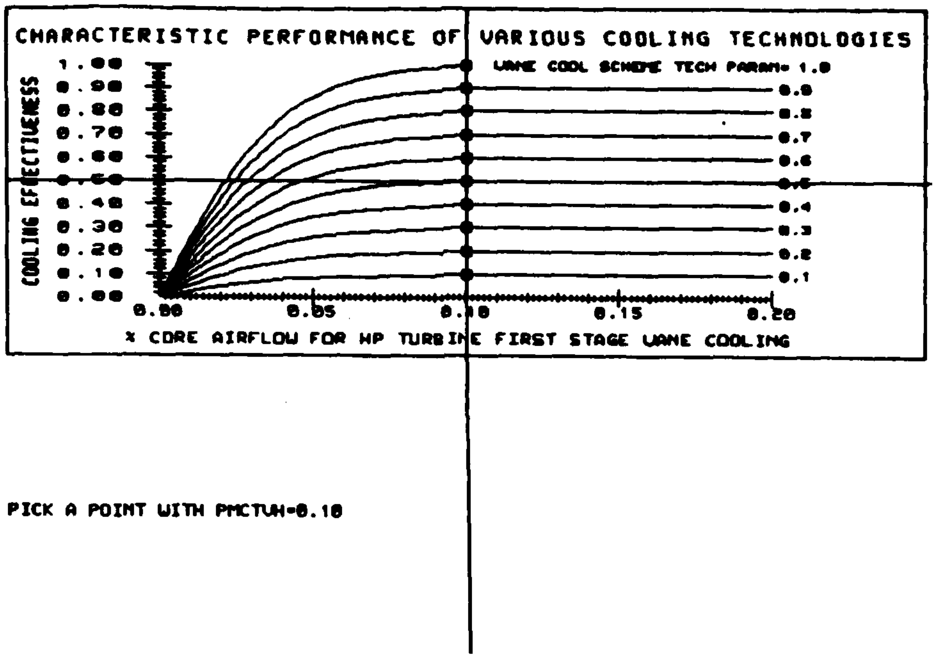


IF THE COOLING TECHNOLOGY LEVEL IS NOT HIGH ENOUGH TO ALLOW THE HOT SPOT ON THE VANE TO BE COOLED TO THE MAXIMUM ALLOWABLE METAL TEMPERATURE SPECIFIED FOR THE VANE, THEN THE PROGRAM PERFORMS CALCULATIONS TO COOL THE BULK METAL TO ITS MAXIMUM ALLOWABLE TEMPERATURE BASED ON EXPOSURE TO THE MIXED STOICHIOMETRIC EXIT/DILUTION GAS TEMPERATURE; T40 GAS MAX ALLOWABLE.

IN OTHER WORDS, THE COOLING SCHEME IS SET UP FOR THE "BULK METAL" OF THE VANE TO REACH THE MAXIMUM ALLOWABLE TEMPERATURE WHILE THE HOT SPOT ON THE VANE IS HOTTER.

HIT RETURN TO GO ON

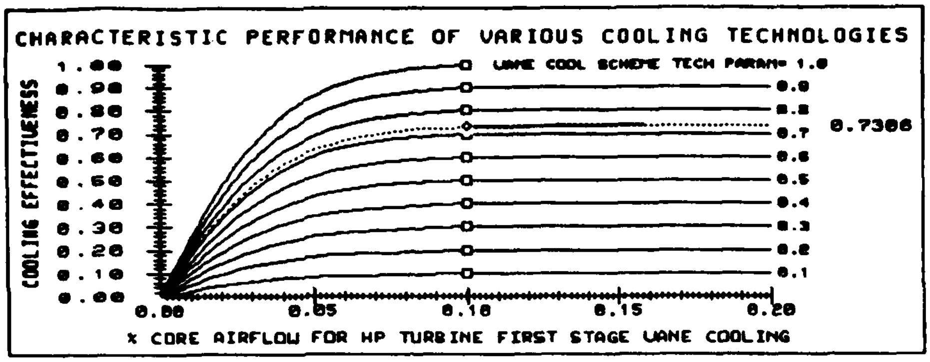
Figure 16c. HP Turbine Vane Cooling Scheme Technology Level



PICK A POINT WITH PMCTUH=0.10

Figure 16d. HP Turbine Vane Cooling Scheme Technology Level

You can move the cursor to any point with PMCTVH = 0.10 and when you hit any key you'll see another curve drawn through the point you chose and labeled with the value of the cooling effectiveness technology parameter off the right hand end. The program then asks whether that value of the parameter is satisfactory. If it isn't you get the cursor back and you can pick a different point. When you are satisfied with the value of CVTECH you picked, answer "yes" and you'll see the next menu.



PICK A POINT WITH PMCTVH=0.10

THAT VALUE OF CVTECH OK? [Y/N]:

Figure 17. The Performance Curve for a Cooling Scheme with Technology Level Parameter = 0.7306

This menu includes all the parameters necessary for TRBOFN to simulate cooling of the high pressure turbine's vanes and rotors. Note that the vane cooling technology parameter is on this menu. That's the value you selected on the last screen. The default values for the airflow and effectiveness of the rotor cooling scheme are set for no cooling. Placing zeros in these parameters results in the program crashing. The vane metal temperature allowable is only important if you chose metal temperature as the control parameter instead of gas temperature.

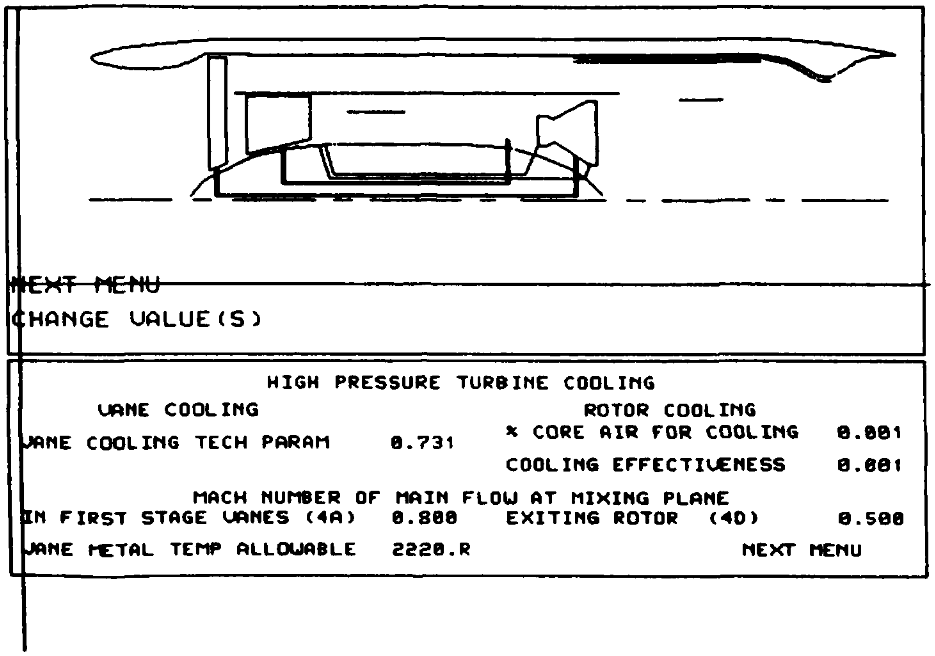


Figure 18a. Menu 7: High Pressure Turbine Cooling Parameters

Figures 18a. and 18b. show the high pressure turbine and the two cooling air ducts highlighted in the engine drawing.

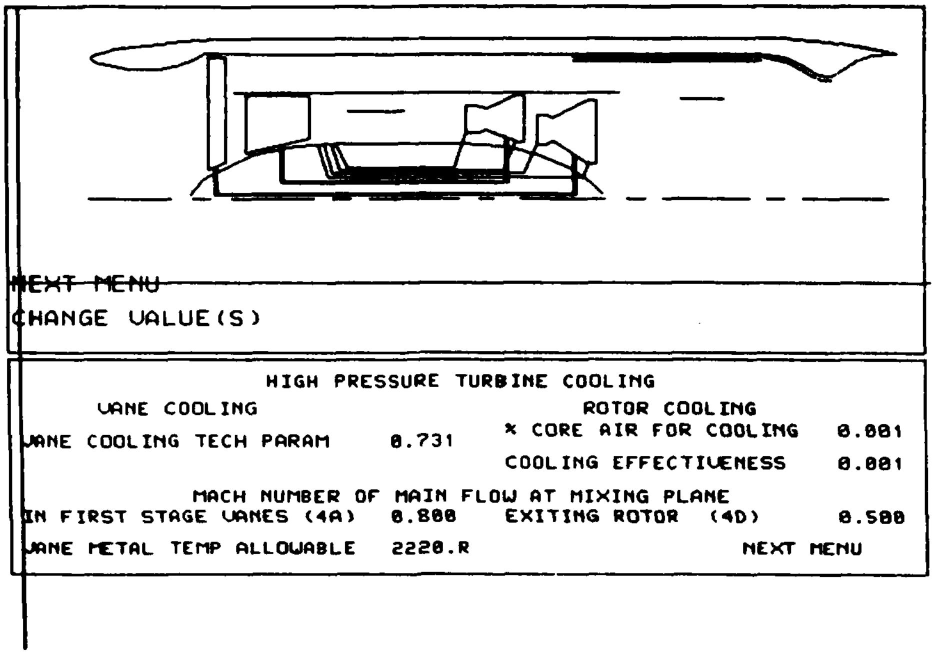


Figure 18b. High Pressure Turbine and Cooling Duct Highlighting

The next menu includes all the parameters necessary for low pressure cooling. The only differences are that the vane cooling scheme is specified by a set value of airflow and effectiveness and there is no option to set metal temperature allowables for the low pressure turbine vanes. Note the low pressure turbine and cooling ducts are highlighted in the engine drawing that accompanies this menu.

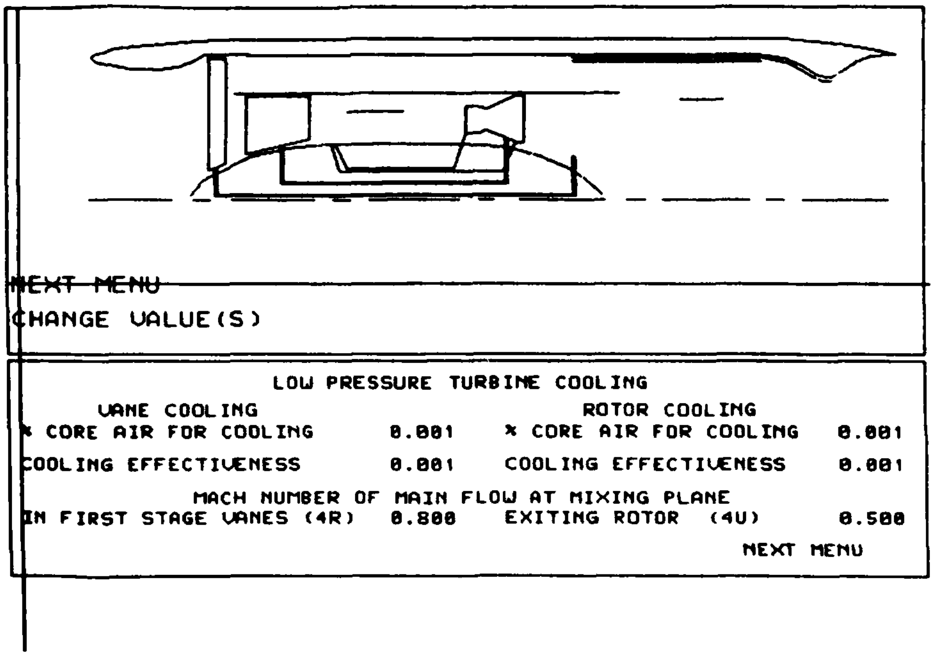


Figure 19. Menu 8: Low Pressure Turbine Cooling Parameters

For mixed flow engine designs, you have the option of having augmented performance calculated. Separate flow designs can not be augmented with TRBOFN. If you do want augmented performance calculated for a mixed flow design then as soon as you answer this question "yes" you will see the next question which appears with Figure 21.

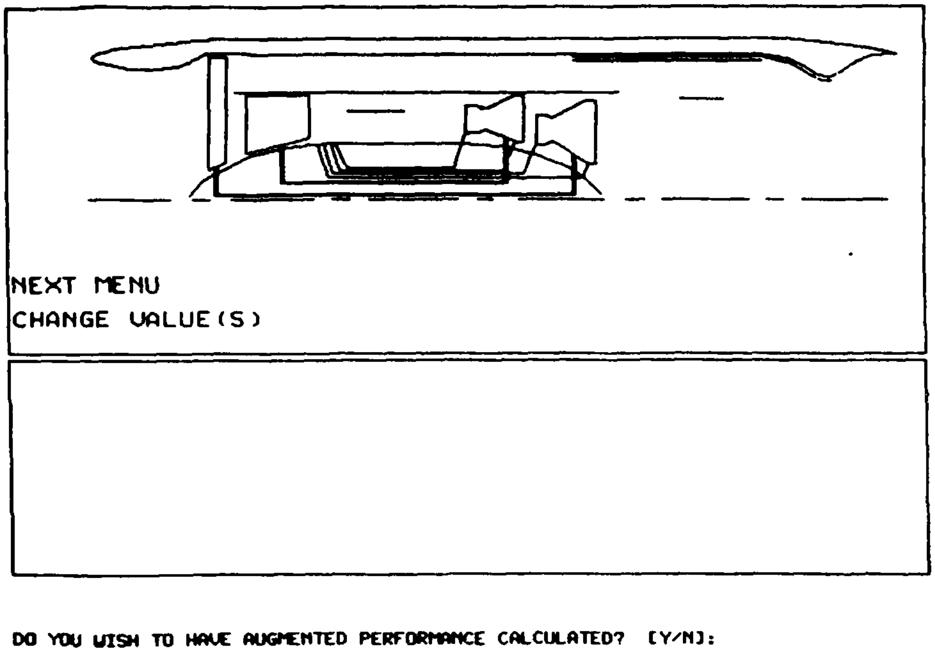


Figure 20. Augmented Performance Option

The number of augmented performance points refers to throttling the afterburner. Entering one point tells the program to simulate only full afterburner; any larger number tells it to first turn on the afterburner full and then throttle it back to a near off condition in that many steps.

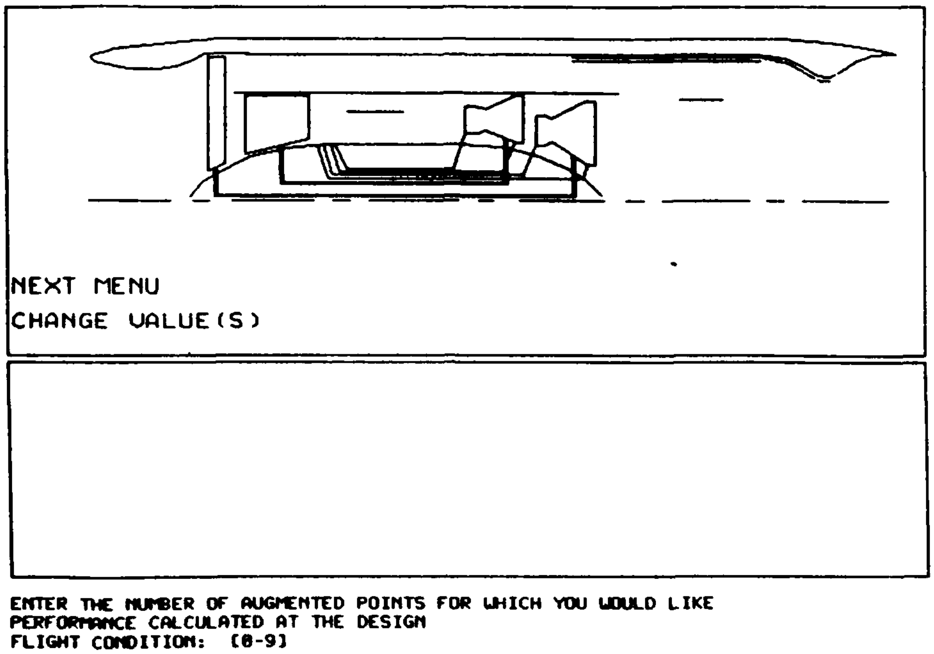


Figure 21. Number of Augmented Points

The next menu allows you to specify how much of the total engine airflow is to be used for nozzle liner and flap cooling. TRBOFN considers these cooling ducts to be open for all operating points for any augmented engine with nozzle cooling. The default values are for no cooling. Once again, entering zeros for these values results in division by zero in TRBOFN. The cooling effectivenesses are for use in calculating the resultant material temperatures of the nozzle liner and flap.

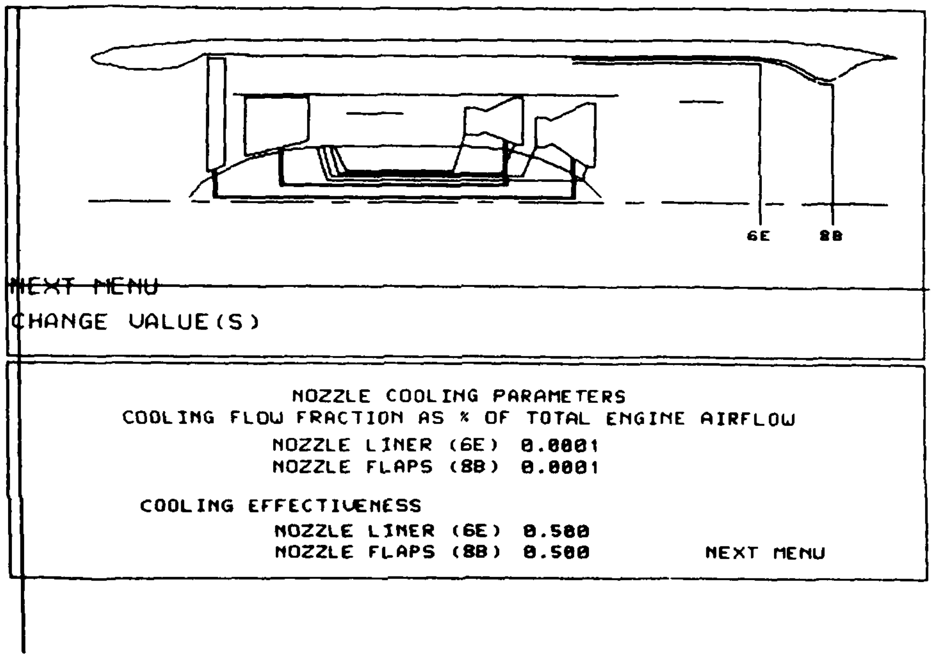


Figure 22. Menu 9: Nozzle Cooling Parameters

The next screen is just an announcement page to tell you that next you get to select the flight conditions where you want performance calculated.

SELECTION OF DESIGN POINT

AND

POINTS FOR OFF-DESIGN PERFORMANCE

FOR ENGINE NUMBER 1

Figure 23. Flight Condition Selection Announcement

In specifying flight conditions for the engine performance program to use, you can specify directly the number of throttled power settings to calculate or you can tell the program to use the flight conditions as maneuver requirements in which case the program will automatically set the number of throttled power settings at which to calculate performance at the maximum value of 19. The maneuver requirement option is useful if you plan to compare several engines with the engine sizing and comparison program, ENCOM. ENCOM compares engines by requiring them to propel an airplane through a series of maneuvers which are specified as sustained accelerations at specific Mach-altitude combinations. If you specify the maneuver requirements you intend to use in ENCOM now, you can be sure your engine performance data files will include the performance information ENCOM will need to do its comparison. Alternatively, if you don't want to use ENCOM, you can specify the number of throttled power settings directly for each flight condition you choose. This will make TRBOFN run faster since it will have fewer performance points to find and calculate.

```
TO SPECIFY OFF-DESIGN FLIGHT CONDITIONS WHERE YOU WOULD LIKE PERFORMANCE CALCULATED

                        YOU HAVE THE OPTIONS OF ENTERING EITHER:

             1.  MANEUVER REQUIREMENTS:  (MACH, ALT, SUSTAINED G  CAPABILITY)

                                         OR

             2.  MACH-ALTITUDE PAIRS WITH NUMBER OF THROTTLED POWER SETTINGS AT EACH


ENTER 1 FOR MANEUVER REQUIREMENTS; 2 FOR MACH-ALT PAIRS:
```

Figure 24. Maneuver Requirements or Mach-Altitude Pairs and Number of Throttled Power Settings at Each

In either case, the next screen you see after answering the question is a plot of Altitude vs Mach number. You can change the limits on the axes to suit your needs very simply by answering the questions as in the sequence depicted in Figures 25a through c. Hitting "RETURN" when the program asks whether you'd like to change the limits on one of the axes is the same as answering "no."

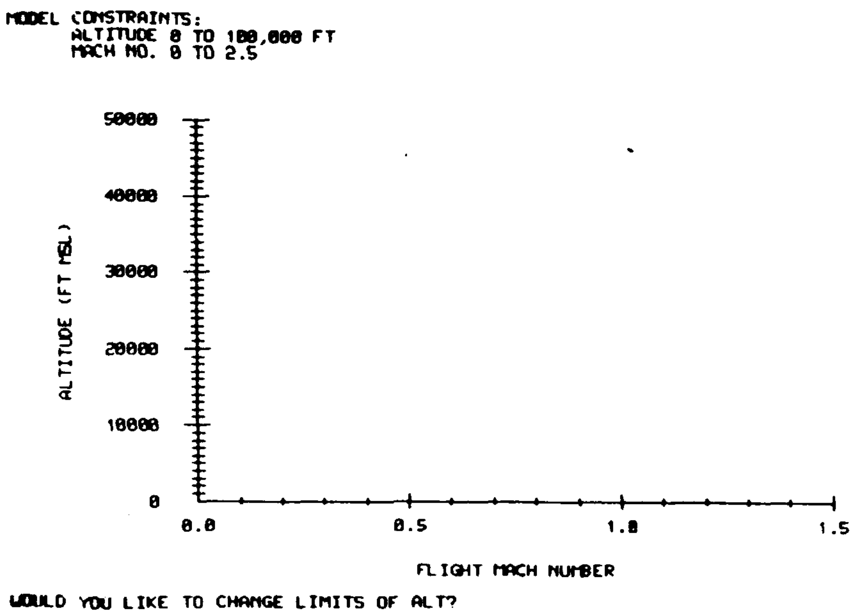


Figure 25a. Changing Limits of Altitude vs Mach Number Space

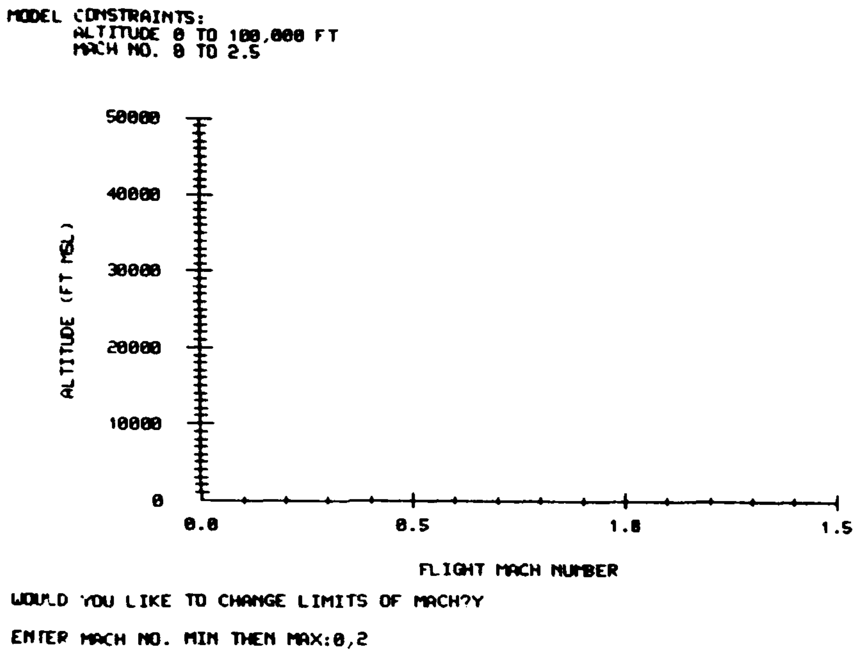


Figure 25b. Changing Limits of Altitude vs Mach Number Space

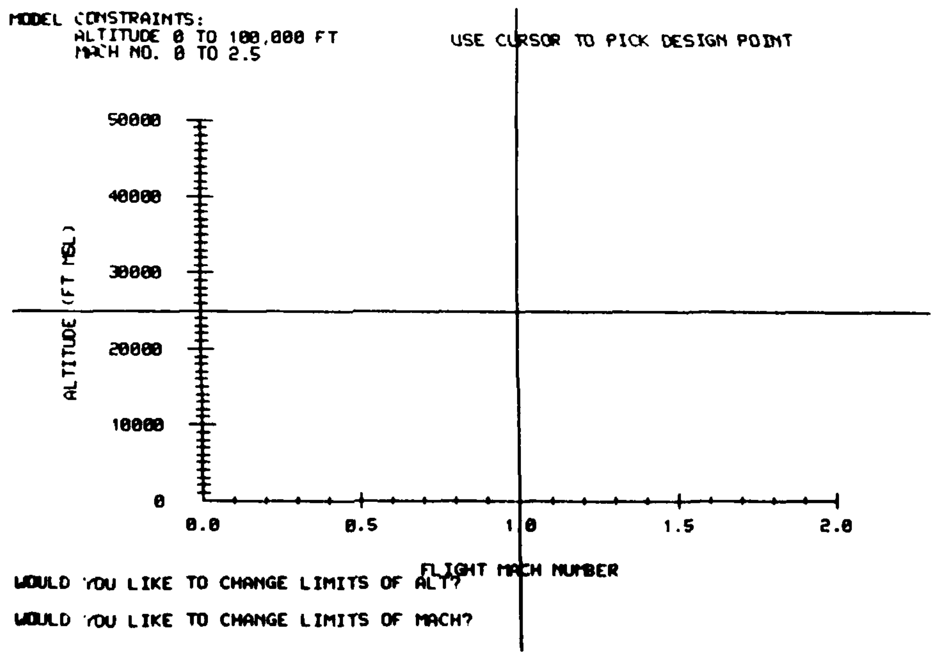


Figure 25c. Changing Limits of Altitude vs Mach Number Space

When you're satisfied with the limits on the axes you get to use the crosshair cursor to select the design flight condition for the engine. Use the thumb wheels on the 4112 terminal to move the cursor to the Mach-altitude you want and press any key. The Mach-altitude pair you picked appears next to the marked point you chose. In addition, a line of constant fan inlet total temperature (T_{20}) is drawn through the point you picked. This is an aid in selecting high and low T_{20} points for off-design operation and for doing a study at constant T_{20}. If the values are not what you thought they would be, you can type in the values you intended by answering the question in the dialog area.

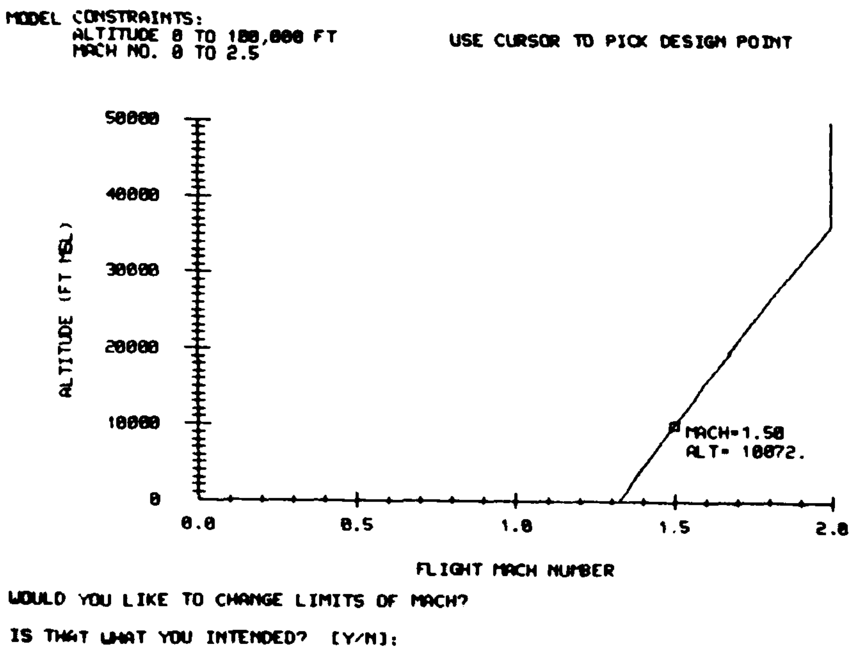
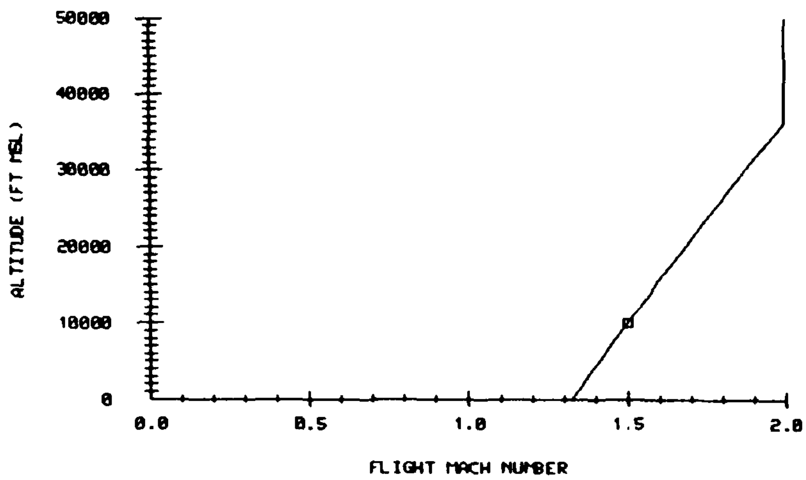


Figure 26. The Design Point and Design Fan Inlet Total Temperature

When you have selected the design point you intended, you get to enter either the number of throttled power settings you want, or the sustained acceleration you want the aircraft to hold at this flight condition, depending on whether you chose to enter maneuver requirements or not.



ENTER THE NUMBER OF THROTTLED POWER SETTINGS FOR WHICH YOU WOULD LIKE PERFORMANCE CALCULATED AT THIS FLIGHT CONDITION: [0-19]:

Figure 27. Number of Throttled Power Settings

If you want to fly the engine through the mission in ENCOM, you need to have TRBOFN calculate performance for the engine at the flight conditions used in the mission profile. SETUP will build the input file to make TRBOFN run the engine at all the necessary flight conditions and it will also make a mission input file to tell ENCOM the maneuver requirements you want the engine to meet if you answer "yes" to the question in Figure 28.

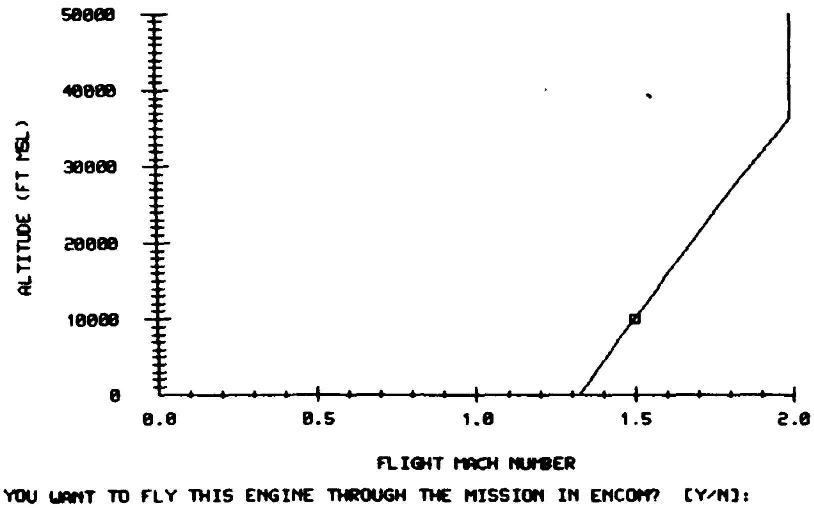
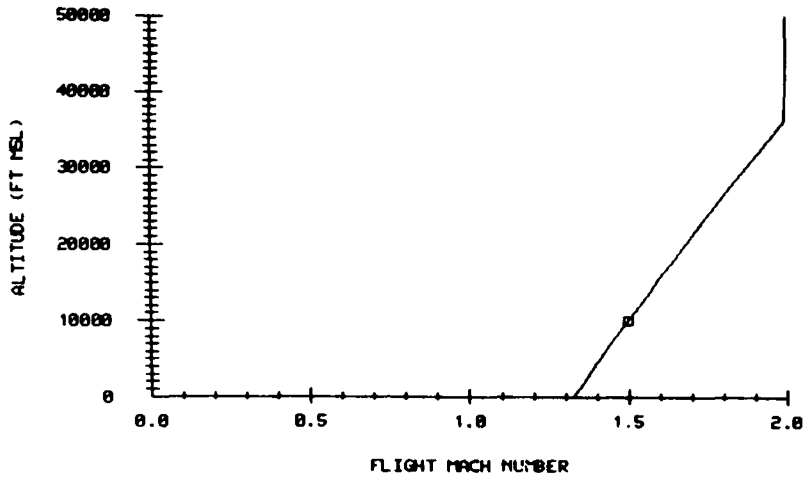


Figure 28. To Build Mission Input File for ENCOM

Either way, you get the option to select more flight conditions if you want to.



DO YOU WANT TO FLY THIS ENGINE THROUGH THE MISSION IN ENCOM? [Y/N]:N

WANT TO PICK OTHER FLIGHT CONDITIONS FOR THIS ENGINE? [Y/N]:

Figure 29. More Flight Conditions

Selecting these off-design flight conditions is just like selecting the design point in that you move the cursor to the desired point, hit a key to encode it, and the program displays the coordinates of the point you picked with a line of constant T_{20} through it and asks you if that was what you intended.

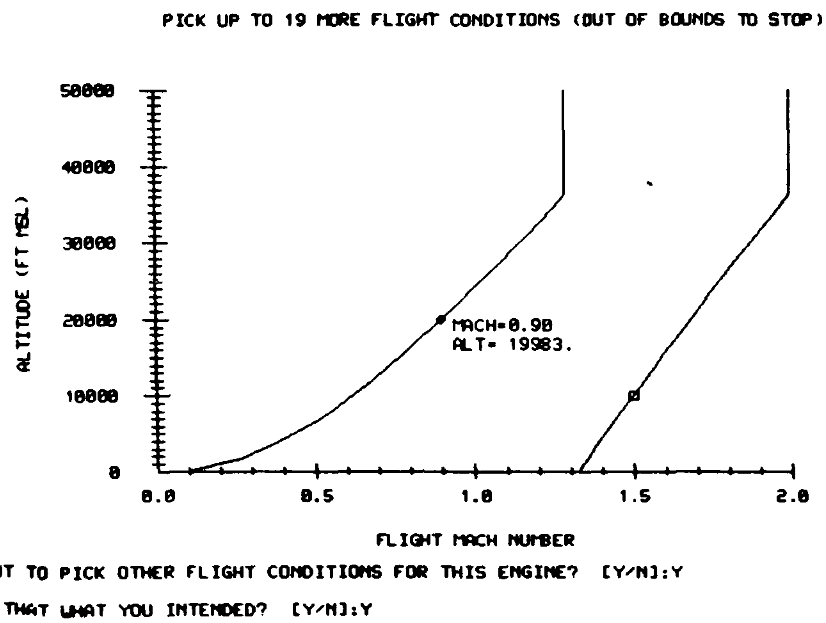


Figure 30. Picking an Off-Design Flight Condition

When you are satisfied with the flight condition on the display, you get to enter the number of throttled qugmentor points you want calculated if your engine is a mixed flow, augmented design.

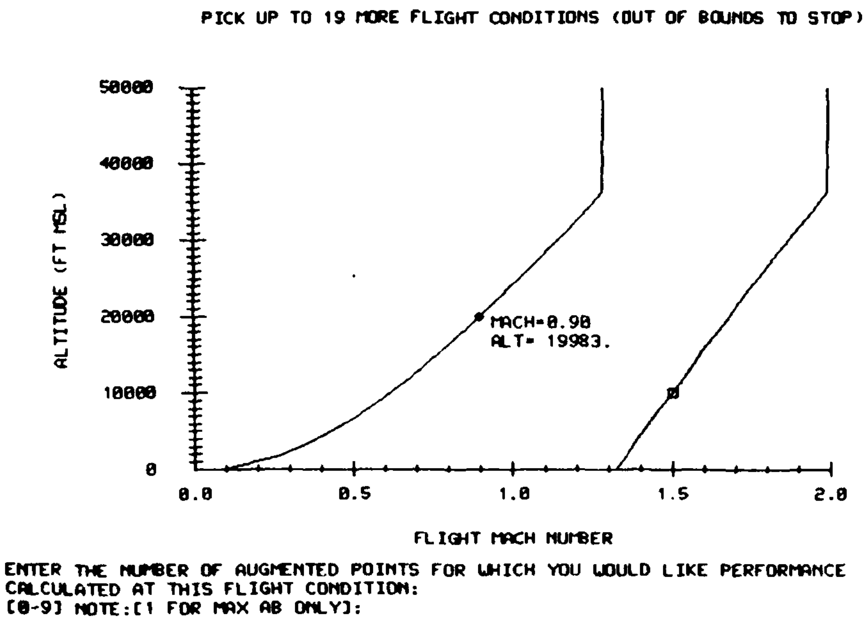


Figure 31. Number of Throttled Augmentor Points

When you have chosen all the off-design points you want (up to 19), pick a point outside the limits of the Mach-altitude axes and the program will erase the graphics screen and ask you for the name you want the data file it makes to have. This is the file that TRBOFN reads to design and calculate performance for the engine you just described.

The output file from SETUP is the input file for TRBOFN. Below is an example:

```
          1
T
 0.9900000       3.000000        0.9000000       6.000000        0.9000000
  1.000000
  135.0000       18500.00        0.5000000       518.6880        6.7762338E-02
 0.4000000      0.4000000        0.1000000      0.1500000
  2220.000       2200.000        T
 0.9000000      0.9000000
 0.5002766      0.8000000        1.0000000E-03  1.0000000E-03  0.5000000
 1.0000000E-03  1.0000000E-03    0.8000000      1.0000000E-03  1.0000000E-03
 0.5000000
T  9.9999997E-05  9.9999997E-05  0.5000000      0.0000000E+00
          5
  1.501172       10071.58                  10            9
 0.6978021       19983.39                  10            9
 0.0000000E+00  0.0000000E+00              10            9
  1.203736       11926.91                  10            9
 0.7958242       40083.06                  10            9
```

The variables that these numbers represent are:

```
NENG
MIXED
PQPDIF        FPR           FEA           CPR            CEA       BR
MWF           FLHV          CPF           TOF            FARSTO
XM20          XM26          XM33          XM50
T40MVA        T40G          CONGAS
THEA          TLEA
CVTECH        XM4A          PMCTRH        ECTRH          XM4D
PMCTVL        ECTVL         XM4R          PMCTRL         ECTRL     XM4U
AUGMNT        PMCNL         PMCNF         ECNL           ECNF
NPAIRS
XM(1)         ALT(1)        NPWR(1)       NAUGPT(1)
XM(2)         ALT(2)        NPWR(2)       NAUGPT(2)
  .             .             .              .
  .             .             .              .
  .             .             .              .
XM(NPAIRS)    ALT(NPAIRS)   NPWR(NPAIRS)  NAUGPT(NPAIRS)
```

The parameters that appear in the data file are in the same order as you entered them while running SETUP. The following list defines all the variable names listed on the last page.

NENG	Number of ENGines for which there is design and off-design information in this file
MIXED	Logical flag to denote mixed (T) or separate (F) flow design
PQPDIF	Fraction of total pressure lost across diffuser due to friction
FPR	Fan Pressure Ratio
FEA	Fan Efficiency, Adiabatic
CPR	Compressor Pressure Ratio
CEA	Compressor Efficiency, Adiabatic
BR	Bypass Ratio (Note: TRBOFN calculates BR for mixed flow designs based on total pressure match between the core and bypass streams at the mixing plane so the value you enter for BR for a mixed flow design is ignored by TRBOFN)
MWF	Molecular Weight of the Fuel
FLHV	Fuel Lower Heating Value (Btu/lb)
CPF	Specific Heat of Fuel
TOF	Entering Temperature of Fuel
FARSTO	Stoichiometric Fuel-to-Air Ratio
T40MVA	Maximum allowable metal temperature of high pressure turbine's first stage vanes
T40G	Maximum allowable gas temperature entering high pressure turbine's first stage vanes
CONGAS	Logical flag: (T) for gas temperature T40G as control limit (F) for metal temperature T40MVA as control limit
THEA	High pressure turbine's adiabatic efficiency
TLEA	Low pressure turbine's adiabatic efficiency
CVTECH	High pressure turbine vane cooling scheme technology level parameter
XM4A	Mach number of main stream at mixing plane for high pressure turbine vane cooling air input
PMCTRH	Percent core Massflow used for Cooling the Rotors of the High pressure turbine
ECTRH	Effectiveness of the Cooling of the Turbine's Rotors, High pressure
XM4D	Mach number of main stream at mixing plane for high pressure turbine rotor cooling air input
PMCTVL	Percent core Massflow for Cooling of the Turbine's Vanes, Low pressure
ECTVL	Effectiveness of the Cooling of the Turbine's Vanes, Low pressure
XM4R	Mach number of main stream at mixing plane for low pressure turbine vane cooling air input
PMCTRL	Percent core Massflow used for Cooling the Rotors of the Low pressure turbine
ECTRL	Effectiveness of the Cooling of the Turbine's Rotor's, Low pressure

XM4U	Mach number of main stream at the mixing plane for low pressure turbine rotor cooling air input
AUGMNT	Logical flag: (T) for augmented engine, (F) for non-augmented engine
PMCNL	Percent total engine Massflow used for Cooling the Nozzle Liner
PMCNF	Percent total engine Massflow used for Cooling the Nozzle Flaps
ECNL	Effectiveness of the Cooling of the Nozzle Liner
ECNF	Effectiveness of the Cooling of the Nozzle Liner
NPAIRS	Number of Mach-altitude Pairs (flight conditions) at which the user wants performance calculated
XM	Array of Mach numbers of flight conditions
ALT	Array of altitudes of flight conditions
NPWR	Array of number of throttled power settings to be calculated at each flight condition
NAUGPT	Array of number of throttled augmentor settings to be calculated at each flight condition

Chapter 3.

TRBOFN: The Ideal Gas Engine Performance Simulation Program

INTRODUCTION:

1. Background: TRBOFN was developed in a project at the Frank J. Seiler Research Laboratory at the Air Force Academy. One of the goals of the project was to develop a method of assessing the relative benefits of various improvements in the technology level of the components of a turbofan engine which was fulfilled by the system documented in this guide. The original engine performance simulation model used in the project was based on perfect gas assumptions including constant specific heats. This proved to be too simple a model for use in this facet of the work. A much more realistic ideal gas model in which the specific heat of the gas is a function of its constituents and its temperature, consistent with the model used by Keeenan, Chao, and Kaye in generating Gas Tables [1], is used in TRBOFN, the engine simulation program described here.

2. Capabilities:

a. Design Parameter Selection: Performance of almost any reasonable cycle turbofan engine can be simulated with TRBOFN. Cycle parameters, a design point (Mach-altitude pair), and up to nineteen off-design flight conditions can be set by the user along with several other parameters. Some of the other user selectable items include:

(1) either mixed flow or separate flow engine design,

(2) whether the engine is to be controlled to gas temperature exiting the burner or to metal temperature in the first stage turbine vanes (Limits for these control temperatures are set by the user.),

(3) use of an alternate fuel (The default fuel is JP4.),

(4) adiabatic efficiencies for the fan, compressor and each turbine,

(5) fractions of core airflow to be used as cooling flows in the high and low pressure turbines' vanes and rotors,

(6) cooling effectiveness and mainstream Mach numbers for each of the four stations where cooling air is mixed with the main flow,

(7) whether augmented performance is to be calculated,

(8) nozzle liner and flap cooling flow fractions and cooling effectivenesses for mixed flow, augmented engines.

b. Off-Design Performance Envelope: Up to nineteen off-design Mach number-altitude combinations can be selected by the user as points for which engine performance information is to be calculated. Performance at the intermediate power setting and at each of up to nineteen throttled power settings is calculated at the design flight condition and at each of the off-design points selected.

3. Constraints and Limitations: Certain combinations of fan pressure ratio, compressor pressure ratio and bypass ratio may result in the design of an engine which is incapable of operating at certain flight conditions. No warning of this is given by the program until it fails. Selection of reasonable engine cycles and operating envelopes should preclude this but it is possible to request the program to simulate performance of an engine that will not operate at the points you requested. In addition to this mode of failure, there are certain limitations to which this program is subject due to the assumptions built into the models. In general, the constraints and limits of the simulation program are as follows:

a. Gas Temperature: No account for dissociation has been made in the ideal gas model. Thus, selection of gas temperatures or metal control temperatures that result in gas temperatures above about 5000 R [2] in the burner will result in an inaccurate representation of the gas properties at stations where the temperature is at or near this level.

b. Flight Mach Number: For simulation of engine performance at Mach numbers above about 2.5 this may not be a reasonable model to use because it does not include an option to account for overboard bleed air and all engine walls are assumed to be adiabatic.

c. Flight Altitude: The limits of the atmosphere model in TRBOFN are the same as the limits of the U.S. Standard Atmosphere, 1962. Standard lapse rates for temperature and pressure are used for calculation of static properties at given altitudes and atmospheric discontinuities are consistent with U.S. Standard Atmosphere tables. Performance at any altitude contained in the U.S. Standard Atmosphere Tables can be simulated.

THE IDEAL GAS MODEL

THE IDEAL GAS MODEL: As mentioned in the Introduction, calculation of the thermodynamic properties of the constituents of air and the products of combustion are performed in the manner outlined by Keenan, Chao, and Kaye in reference 1. Several constants for the constituent gases were taken from references 3, 4, and 5. The approach is based on the assumption that the mechanics of the gas molecules' energy storage can be described statistically based on the make-up of the gas and its temperature. The following sections describe this approach very briefly. A detailed description of all the calculations that result in the ideal gas model is contained in Keenan, Chao, and Kaye's book and each calculation is also documented in the GAS model subroutines.

1. The Make-up of the Gas in the Engine: Air is taken to be a mixture of the following gases in the stated proportions:

N_2 (Nitrogen)	78.03% by volume
O_2 (Oxygen)	20.99% by volume
Ar (Argon)	0.98% by volume

The proportions of the products of combustion CO_2 (Carbon Dioxide) and H_2O (Water Vapor) at any given station in the engine depend on the fuel-to-air ratio at the station of interest which depends on the amounts of dilution and cooling air mixed into the flow downstream of the stoichiometric combustion section of the burner.

2. The Gibbs-Dalton Relation: The Gibbs-Dalton Relation simply states that the properties of a mixture of several different gases can be calculated as the sum of the mole fraction weighted contributions of the constituents. This relation is used in the calculation of the thermodynamic properties of various air/products-of-combustion mixtures. The molecular weights of the constituents of air and the products of combustion follow:

	Molecular Weight (gm/mole)
Ar (Argon)	39.9480
N_2 (Nitrogen)	28.0134
O_2 (Oxygen)	31.9988
CO_2 (Carbon Dioxide)	44.01
H_2O (Water Vapor)	18.01534

3. <u>Calorically Imperfect Gas:</u> A calorically imperfect gas obeys the equation of state

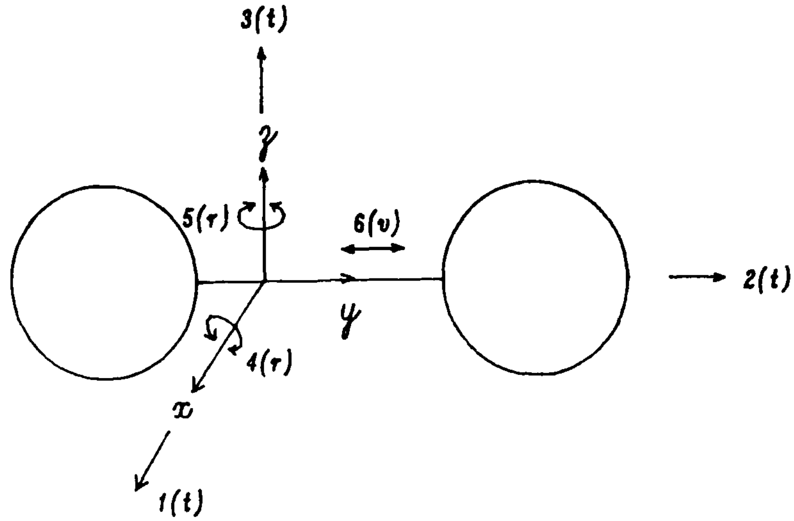
$$P_s V = RT_s \qquad \text{where } P_s = \text{static pressure}$$
$$V = \text{volume}$$
$$R = \text{Universal Gas Constant}$$
$$T_s = \text{static temperature}$$

which makes it a thermally perfect gas. A calorically imperfect gas also has specific heats (at constant pressure, c_p; and at constant volume, c_v) which are functions of temperature only with

$$c_p - c_v = R.$$

4. <u>Gases Made up of Monatomic Molecules:</u> Argon is the only constituent gas made up of monatomic molecules whose properties are accounted for in the gas modeling subroutine MONATOM. The functions relating c_p and c_v to temperature for gases made up of monatomic molecules are derived from the classical theory of equipartition of energy. This theory states that equal amounts of energy are stored in each of the mechanical processes available to the molecules to store energy, provided a large enough number of molecules is considered. Each mechanical process is called a degree of freedom. Monatomic gas molecules have three degrees of freedom, all translational. The equipartition of energy theory leads to c_p and c_v being independent of temperature which implies that caloric imperfections for monatomic gases are small. This agrees well with experimental determination of the specific heats for gases made up of monatomic molecules.[2]

5. <u>Gases Made up of Diatomic Molecules:</u> The properties of gases made up of diatomic molecules (e.g., O_2 and N_2) are based on a statistical thermodynamic model which uses energy storage distributions based on temperature. Diatomic molecules have six degrees of freedom. Consider the dumbell shaped molecular structure in Figure 1.



(t) = translational (r) = rotational (v) = vibrational

Figure 1. Diatomic Molecule's Six Degrees of Freedom

Its six degrees of freedom include three translational modes (along the x,y and z axes), two rotational modes (about the x and z axes; the moment of inertia of a molecule with this structure about its longitudinal axis is negligible compared to its moment of inertia about either of the other two normal axes) and one vibrational mode. An anharmonicity correction term is included to correct for errors introduced by assuming the molecule acts as a rigid rotator and harmonic oscillator. The distribution of energy stored by each of these six degrees of freedom depends on the temperature at which thermodynamic properties are to be calculated. At low temperatures, the contributions of rotation and vibration are negligibly small compared to the contributions of translational modes. At moderate temperatures, the contribution of vibration to energy storage is still small while rotational modes are dominant and translational modes are fully active. The characteristic temperatures at which new modes become active have been found empirically and documented in reference 5. The model for oxygen also accounts for electronic excitation above a characteristic temperature, also taken from reference 5.

6. Gases Made up of Triatomic Moelcules: The most complex gas molecules accounted for in this simulation are triatomic H_2O and CO_2. The statistical quantum mechanical approach to calculating thermodynamic properties of triatomic gases was viewed as too complicated and poorly documented to pursue. We opted instead to use the equations to account for the contributions of translational, rotational and vibrational energies and to add to them an appropriate contribution due to electronic excitation so that the properties calculated would match the tabulated data in the Gas Tables book. In using these equations to get the best possible curve fits we used the documented values for characteristic temperatures for rotation and vibration for each molecule. Using this much of the model we could match the portion of each curve below the higher of these two temperatures very well. To model the rest of the curve, however, we had to simplify the accounting for electronic excitation. The simplification involved treating all electronic excitation modes as a group and iterating to find an artificial characteristic temperature to give the most accurate curve fits for the tabulated properties. Figure 2 shows representations of the structure of both water vapor and carbon dioxide molecules.

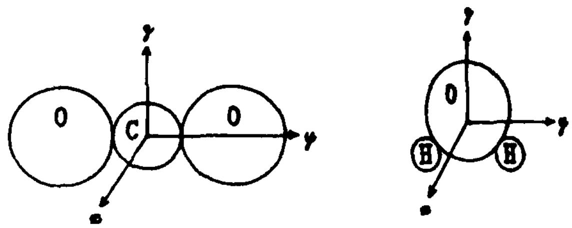


Figure 2. Water Vapor and Carbon Dioxide Molecular Structures

Note that the carbon dioxide molecule is linear and therefore has three translational and two rotational degrees of freedom. Water vapor, on the other hand, has three translational and an additional third rotational degree of freedom due to its non-linear structure. Figure 3 shows the close agreement between the tabulated data from Keenan, Chao and Kaye and the curve fits we generated.

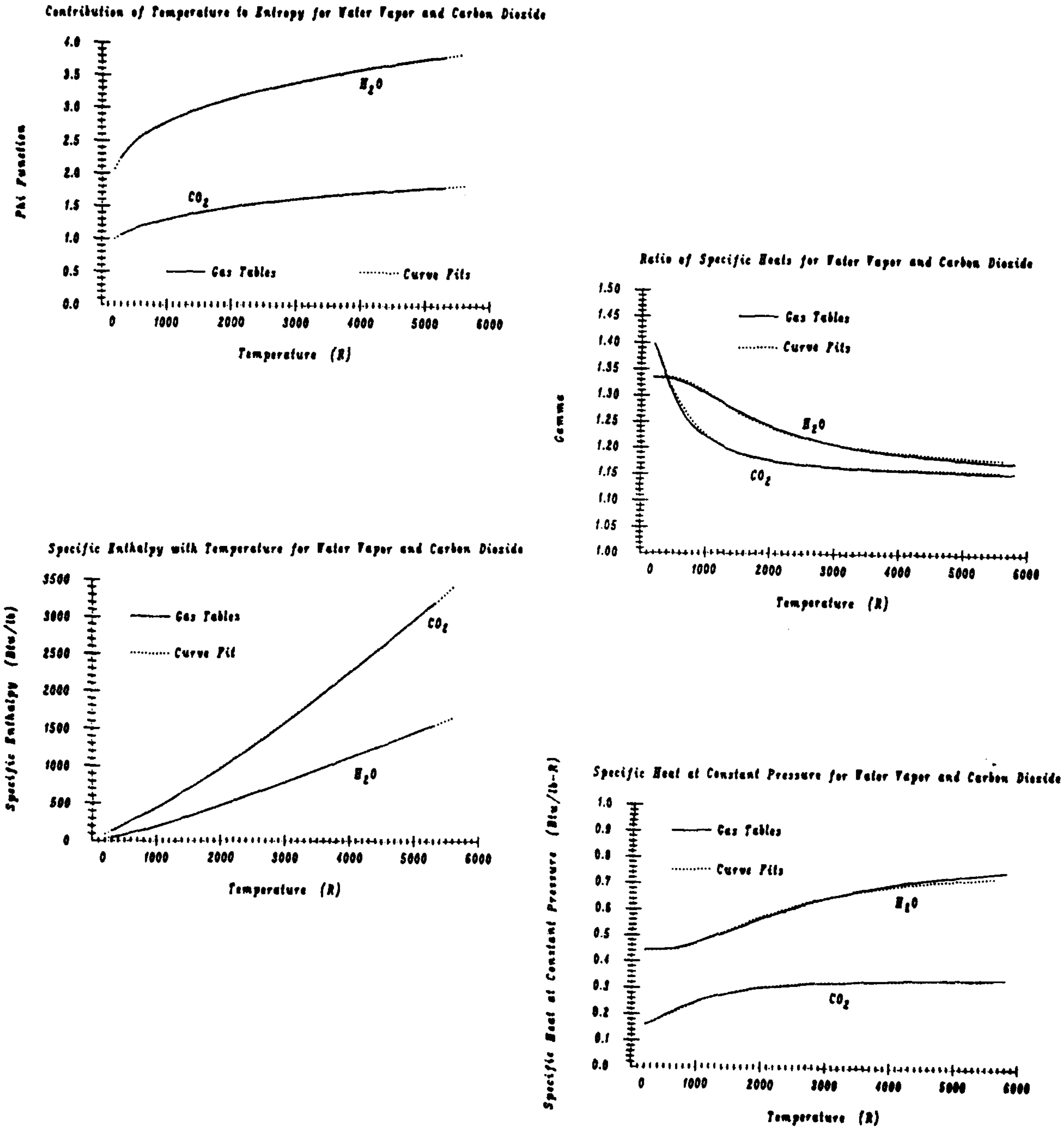


Figure 3. Agreement Between Tabulated Data and Curve Fits

ENGINE COMPONENT MODELS

ENGINE COMPONENT MODELS: TRBOFN's program structure is modular. That is, each engine component is modeled in a separate subroutine. The purpose of this section is to present information regarding the development of the component model subroutines.

1. Overview of the Engine Model: Figures 4a and b are schematic drawings of the two types of engines whose performance can be simulated by TRBOFN. Figure 4a depicts a mixed flow engine; Figure 4b, a separate flow engine. Following the drawings is a list describing the station number designations.

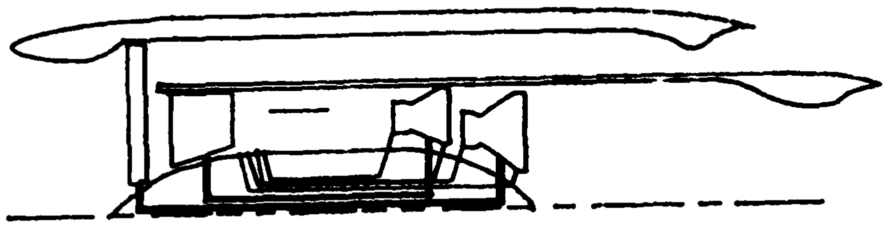


Figure 4a. Schematic of a Mixed Flow Engine

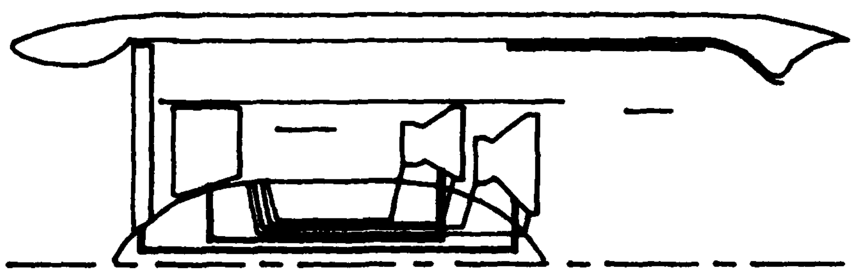


Figure 4b. Schematic of a Separate Flow Engine

STATION NUMBER DESIGNATIONS:

20-Series Compression System

20	Lp Compressor Entrance
23	Lp Compressor Exit
24	Lp Compressor Exit after Bypass Diverted
26	Hp Compressor Entrance
29	Hp Compressor Exit

30-Series Heat Addition System

30	Entry after LPT Cooling Airs Diverted
31	Entry after HPT Cooling Airs Diverted
33	Primary Burner Entry after Dilution Air Diverted and Primary Diffused
34	Primary Burner w/Fuel Mixed
36	Primary Burner Burned-stoich
3D	Dilution Air Entry
38	Burner Exit - Mixed Primary and Dilution

40-Series Turbine System

40	Hp Vane Entrance
4A	Mainstream at Vane Cooling Air Entry
4B	Cooling Flow at Vane Cooling Air Entrance
4C	Mixed-Mainstream and Cooling
41	Choke Point
42	Hp Rotor Entrance
4D	Mainstream-Blade Cooling Entrance
4E	Cooling Air-Blade Cooling Entrance
4F	Mixed-Mainstream and Cooling
46	Lp Vane Entrance
4R	Mainstream-Vane Cooling Entrance
4S	Cooling Air-Vane Cooling Entrance
4T	Mixed-Mainstream and Cooling
47	Choke Point
48	LP Rotor Entrance
4U	Mainstream-Blade Cooling Entrance
4V	Cooling Air-Blade Cooling Entrance
4W	Mixed-Mainstream and Cooling
4X	After Fan ID Lp Work Extracted
4Y	After Other Engine Related Lp Work Extracted
4Z	After Fan OD Lp Work Extracted
49	Lp Turbine Exit-After Customer Lp Work Extracted

50-Series Mixer System

50	Core Entrance
15	Bypass Entrance
59	Mixer Exit

60-Series Augmentor System

60	Entrance
63	Primary-Dilution Air Diverted
64	Primary-Mixed w/Fuel
66	Primary-Burned
6D	Dilution Air Return
67	Mixed Mainstream also Liner Cooling Air Return
6E	Cooling Air - Liner Cooling Air Return
68	Mixed
69	Exit

70, 80, 90-Series Nozzle System

70	Nozzle Entrance
80	Throat
8A	Mainstream at Liner Cooling Air
8B	Cooling Air - Liner Cooling Air
8C	Mixed Mainstream
90	Exit Plane

10-Series Bypass System

15	Bypass Return to Mixer if Mixed Flow Engine
18	Bypass Nozzle Throat if Separate Flow Engine
19	Bypass Nozzle Exit if Separate Flow Engine

Several smaller section schematics for engine components are included in the following sections to illustrate the modeling assumptions for each component.

1. The Diffuser: The total pressure recovery through the diffuser accounts for two loss mechanisms:

a. Friction: The total pressure loss due to frictional effects is accounted for as a user-selected fractional pressure drop assumed to be constant with Mach number and altitude.

b. Shock Losses: The total pressure loss due to shocks is accounted for in accordance with MIL 5008-C:

$$P_3 = (P_2)\,(1 - (.075)(M-1)^{1.35}) \quad \text{where } P_3 = \text{pressure after loss}$$

P_2 = pressure before loss

M = flight Mach number

for flight Mach numbers greater than 1.0.

These calculations are performed in the subroutine RAMREC.

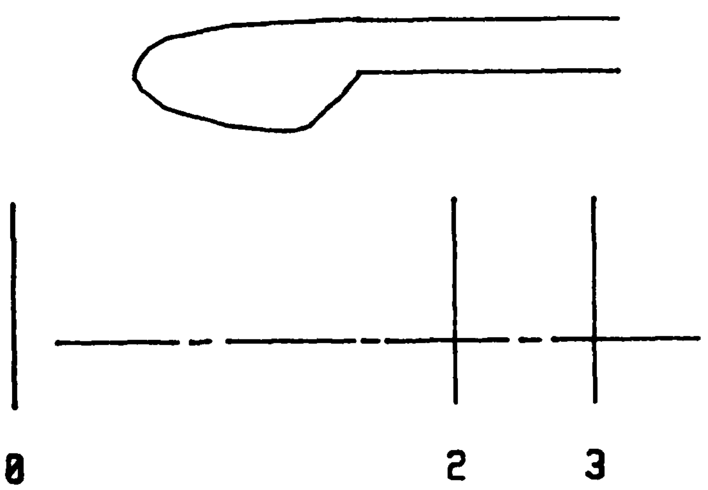


Figure 5. Diffuser Model

Calculation of other total thermodynamic properties after diffusion based on free stream statics and flight Mach Number is performed in the subroutine RAM.

2. The Fan and Compressor: The compression processes performed by the fan and compressor components are assumed to be adiabatic. Thus, each component has an adiabatic efficiency associated with it which, for a compression process, is defined as the ratio of the enthalpy required for an isentropic compression process (i.e., at constant entropy, "s") to that required to perform the same compression adiabatically. These processes can be described by paths on a plot of enthalpy versus entropy, an H-s diagram. Paths 1 and 2 on Figure 4 are lines of constant pressure where P_2 is greater than P_1. Path 3 represents the isentropic (or constant-s) compression process between P_1 and P_2 and path 4 represents the adiabatic compression between the same two pressures. Thus, the definition of the adiabatic efficiency can be written as

$$\eta_{a_c} = \frac{H_{isentropic}}{H_{adiabatic}} = \frac{H_{2s} - H_1}{H_2 - H_1}$$

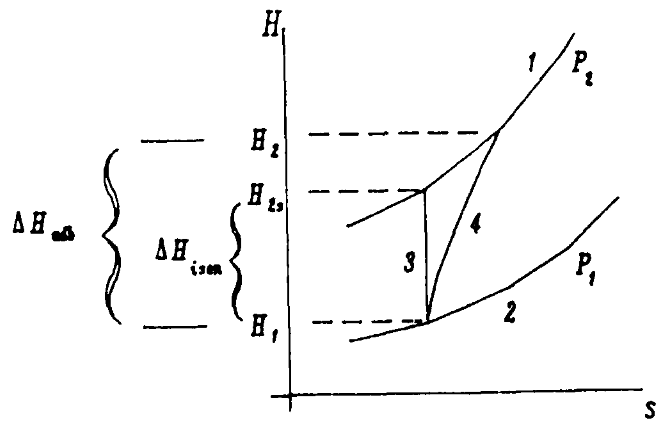


Figure 6. H-s Diagram for Compression Processes

Because of the fact that isentropic processes cause no increase in entropy and that adiabatic processes do result in increased entropy, $H_2 - H_1$ will always be greater than or equal to $H_{2s} - H_1$ for adiabatic compression processes because the constant pressure lines diverge on the H-s diagram. The adiabatic efficiency of the processes, therefore, will always be less than one. The component adiabatic efficiencies for the fan and the compressor are user input parameters and are assumed to be constant at all operating points.

Two subroutines are used to simulate the effects of the compression devices: CMPRSS and CMPRSR. CMPRSS calculates the enthalpy required to perform a specified compression with a given adiabatic efficiency. CMPRSR, on the other hand, calculates the pressure rise based on the enthalpy input to the compression device and its component adiabatic efficiency.

3. <u>The Burner Section</u>: Airflow exiting the compressor has four cooling flows ducted off to be used for high and low pressure vane and rotor cooling in the turbines before it enters the burner section of the engine at station 31. When it reaches station 33 it encounters a splitter plate. Some of the flow then goes through the stoichiometric combustion chamber from station 33 to 36 and the rest is ducted around for use as dilution air. The dilution air and the products of stoichiometric combustion are then mixed to form the burner exit flow.

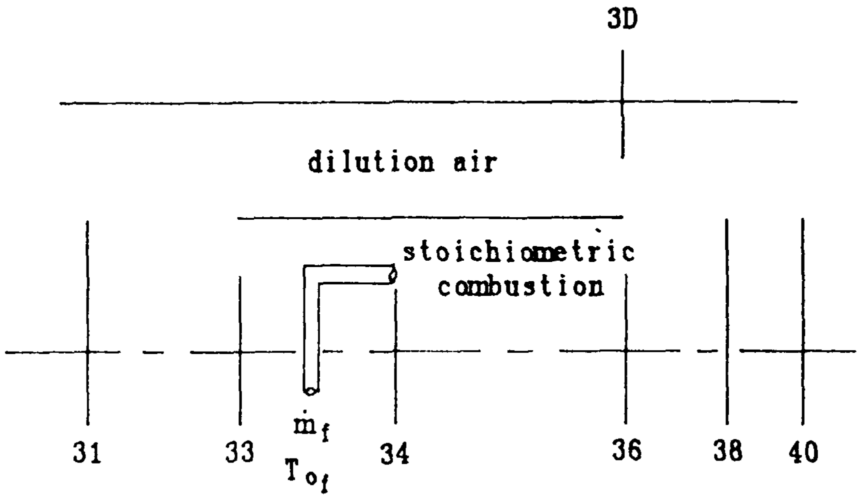


Figure 7. The Burner Section Model

The Dilution Fraction: The fraction of total burner air used for dilution (PMBDL in the program: Percent Massflow, Burner DiLution) is determined in the following ways for the three modes of engine operation:

a. Design: In the DESIGN subroutine this fraction is determined through an iterative process so that the temperature of the flow that results from the mixing of dilution air with the stoichiometric combustor exit is at its specified maximum allowable value. This maximum allowable value can be specified in either of two ways.

(1) For a control scheme based on gas temperature, the temperature exiting the burner at station 38 can be specified directly since the flow from station 38 to station 40 where it first enters the turbine vanes is assumed to be adiabatic.

(2) For a control scheme based on turbine metal temperature, the maximum allowable gas temperature exiting the burner is calculated from the maximum allowable metal temperature, the temperature and amount of cooling flow being used for the first stage vanes in the high pressure turbine and the cooling effectiveness for the manner in which they are being cooled.

b. Off-Design: For cases where operation at an off-design flight condition is to be calculated, the burner dilution fraction which causes one of the control parameters to meet its constraint (i.e., fan or compressor physical or corrected speed reaching 100% of its design value or first stage turbine vane metal or turbine inlet gas temperature reaching its design limit) while all the others are less than their limiting values is determined through an iterative routine, OFFDSG.

c. Throttled Power Settings: The fraction of burner air used for dilution is incrementally increased from its value at intermediate power to a calculated maximum to simulate performance at the requested number of throttled power settings. Each incremental step is one twentieth of the difference between PMBDL at intermediate power and the calculated maximum. The maximum value of the burner dilution fraction corresponds to an "idle" power setting. PMBDL for "idle" is calculated with a formula in subroutine THROTL which was derived "empirically" through many runs of the program TRBOFN for many different engine designs to determine the maximum burner dilution fraction that allowed the engines to run.

The Stoichiometric Combustor: The stoichiometric combustion chamber in the engine model is the section between stations 33 and 36. Between stations 33 and 34 heat is being transferred from the air to the fuel until their temperatures are equal. From station 34 to 36, the stoichrometric chemical reaction between the fuel and the oxygen in the air takes place. The thermodynamic effects of this reaction are accounted for in subroutine STOICH. The stoichiometric fuel-to-air ratio is determined by the ratio of carbon and hydrogen atoms in the fuel molecules to the number of oxygen atoms required to complete the chemical reaction from fuel and oxygen in the air to water vapor and carbon dioxide. The stoichoimetric burning of the fuel results in no oxygen molecules being

left in the products of combustion at station 36. In the burner model the specific enthalpy of the products of stoichiometric combustion is determined based on the fuel lower heating value and the stoichiometric fuel-to-air ratio. This quantity is used as one of the inputs to the calculation in which the effects of mixing dilution air ducted from the compressor exit are determined.

Dilution Air Mixing: The mixing of the dilution air stream (station 3D) with the hot gas stream exiting the stoichiometric combustion chamber at station 36 to form the stream at station 38 may be performed by one or more members of a set of subroutines. When the desired exit gas temperature (T_{38}) is known, as in the design case, then the subroutine DILUTE iterates to find the burner dilution air fraction that results in the exit stream having the specified temperature. If, on the other hand, the burner dilution air fraction is specified (as at throttled power settings and during iterations to find the intermediate power setting at some off-design flight condition) then the MIX... subroutines performs the calculations to mix the two streams.

4. The Turbine Section: Both the high pressure turbine and the low pressure turbine are modeled in exactly the same way. Figure 8 is the schematic representation of the high pressure turbine model.

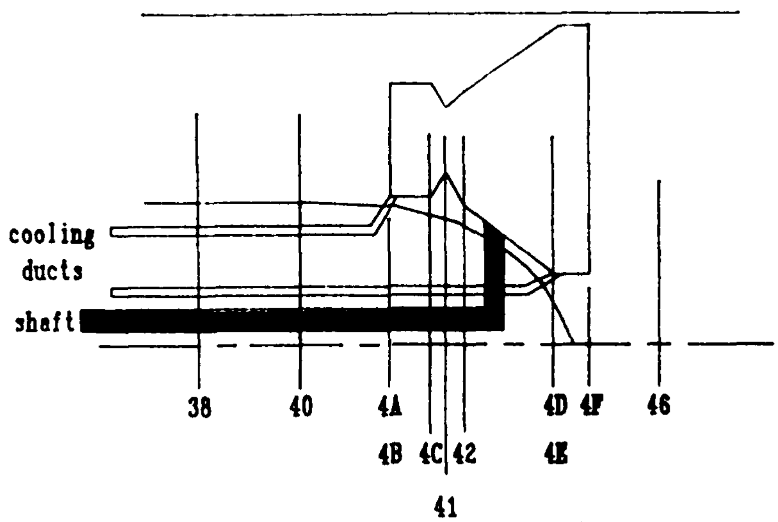


Figure 8. High Pressure Turbine Model

Station 40 is the turbine section entrance. The turbine's vane cooling is modeled as a constant area mixer in which the main stream at station 4A is mixed with cooling air which was ducted around the burner section from just behind the compressor to station 4B. The mixture of these two streams forms the stream at station 4C. Station 41 is the choke point in the first stage vanes which is modeled as a constriction. Station 42 is the entrance to the work extraction section, the rotor, which ends at station 4D. Station 4D is also the entry plane of the mainstream to the rotor cooling model. The mixing of cooling air at station 4E with the mainstream at 4D is modeled in exactly the same manner as the vane cooling. The exit stream formed by this mixing is the exit stream from the turbine since the flow undergoes no further changes to station 46.

Basis for Turbine Section Model: Engines with cooled turbine parts generally make use of similar cooling schemes. Typical designs of cooled turbine guide vanes make use of film cooling. The cooled vanes are upstream of the section that performs the work extraction, the rotor. Most rotor cooling schemes rely on internal convection to do most of the cooling by ducting most of the cooling air through the hollow rotor blades and blowing it out their trailing edges. For a single stage turbine, then, the work extraction process is performed on gas flow that includes the air that was used to cool the vanes but not the rotor cooling air. The turbine section model accounts for these assumptions relative to realistic cooled turbine designs in the following ways:

(1) The constant area mixing model balances enthalpy, momentum and mass flow between the two input streams and the exit stream before the work extraction calculation to simulate the effects of vane cooling on the flow from which the rotor must extract work.

(2) The vane metal temperature is calculated based on the temperature and amount of the cooling air, the temperature of the hot gas to which the vane metal is exposed, and the cooling effectiveness of the cooling scheme. The cooling effectiveness for each of the four cooling processes in the turbines are user-selected and assumed to be constant for all operating points.

Cooling effectiveness is a measure of how well a particular cooling scheme works based on a ratio of temperature differences. It is defined as the ratio of the difference between temperatures of the cooled metal and the cooling gas to the difference between the temperatures of the hot gas and the cooling gas, or:

$$E_c = \frac{T_{hot\ gas} - T_{metal}}{T_{hot\ gas} - T_{cool\ gas}}$$

As an example of the correlation between technology level and cooling effectiveness, a current technology engine's high pressure turbine vane cooling scheme could result in a cooling effectiveness of about 73% using just over 8% of the core airflow for cooling.

(3) After the work extraction calculations are performed on the stream that includes the gas flow entering the turbine section plus the vane cooling flow, the turbine rotor cooling flow is mixed into the stream. This mixing is modeled by assuming it takes place in a constant area duct in which the mass flow, enthalpy and momentum of the exit stream all balance with the sums from the two entering streams.

Turbines as Work Extraction Devices: Both turbines have user selectable component adiabatic efficiencies associated with them. These efficiencies are assumed constant regardless of the operating point just as those associated with the fan and compressor. The definition of the adiabatic efficiency for an expansion process is the ratio of the enthalpy extracted in an adiabatic expansion process to that collected in an isentropic expansion with the same pressure drop. On Figure 9, another H-s diagram, lines 1 and 2 are lines of constant pressure where P_1 is higher than P_2.

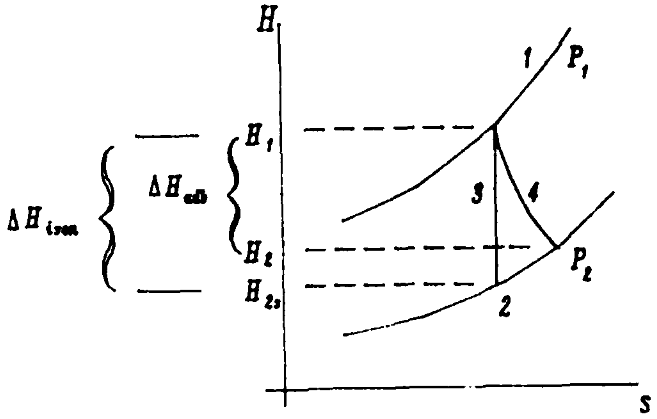


Figure 9. H-s Diagram for Expansion Processes

Path 3 describes the isentropic (constant-s) expansion from P_1 to P_2 and path 4 describes the adiabatic expansion between the same two pressures. The definition of the adiabatic efficiency of an expansion process can then be expressed as:

$$\eta_{a_e} = \frac{H_{adiabatic}}{H_{isentropic}} = \frac{H_1 - H_2}{H_1 - H_{2s}}$$

Since the most efficient expansion process is the constant-s path shown as path 3, and inefficient processes result in increased entropy, the turbine adiabatic efficiency must always be less than or equal to one. Two subroutines perform the calculations to simulate the effects of the turbines: TURBIN and TURBND. TURBND is used to calculate the turbine

expansion ratio when the work output required (delta enthalpy, H) is known and the adiabatic efficiency is specified. This is used in the design case when the compressor and fan pressure ratios are specified. TURBIN calculates the work output based on a given value for the turbine expansion ratio and a specified component adiabatic efficiency. This is used for all off-design operating conditions.

Turbine Vane and Rotor Cooling: All flow cooling processes in the turbines are modeled in exactly the same way by the MIX... subroutines. Members of that series of subroutines calculate total and static thermodynamic properties of the mixture of two streams based on:

1. Known totals and static conditions and the constituent make-up of the main stream.
2. Known total conditions in the cooling stream.
3. Known flow fraction used for cooling (assumed constant)
4. Requiring the static pressures of the two streams to be mixed to be the same at the mixing plane.
5. Conservation of Massflow.
6. Conservation of Energy (to get the total conditions).
7. Force - Momentum Balance (to get the static conditions). Force = 0 since walls are parallel due to the constant area assumption.

5. The Augmentor: Only mixed flow engines can be augmented in this program. The augmentor model is very similar to the burner model in that the afterburner of the engine is treated as two ducts: one for stoichiomertic burning and one for dilution. The major difference is that the input stream to the afterburner is not pure air but rather a stream that contains some products of combustion already. Figure 10 is a schematic representation of the afterburner model. Note the similarity between this and Figure 7, the burner section model.

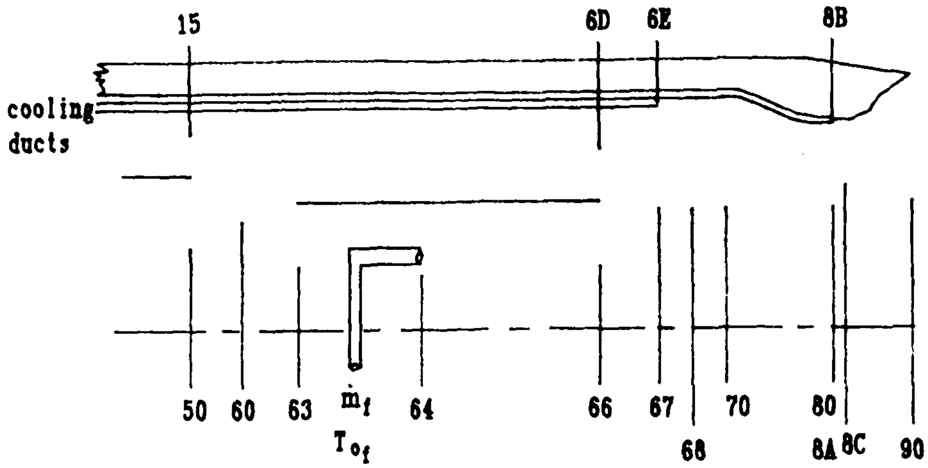


Figure 10. The Afterburner Model

Stations 63 through 66 are analogous to stations 33 through 36 in the burner model. The fuel is heated by the air between stations 63 and 64 and it is burned stoichiometrically with the oxygen in the entry stream between stations 64 and 66. Subroutine AFBRNR calls subroutine STOICH to perform these calculations. The MIX... subroutines are used to account for the mixing of the stoichiometric combustor exit and the dilution streams. Likewise, these MIX... routines are used to account for the return of the nozzle liner and flap cooling streams at stations 6E and 8B.

6. <u>The Nozzle</u>: The nozzle is modeled as a reduced area section for the flow to pass through. Its throat area is calculated in subroutine DESIGN as that which chokes the flow at the design flight condition. At off-design flight conditions it is not always choked but it does, however, always adjust the flow for perfect expansion into the atmosphere at all flight condition, including design. In other words, the throat area, A80, is always held constant for throttled or off-design operation but the exit area, A90, varies appropriately so the flow is always perfectly expanded. This also holds true for the bypass nozzle for separate flow engines. When the afterburner is turned on, both the nozzle throat area and the exit area are changed to allow the additional massflow to pass and to be perfectly expanded. The MIX... subroutines are used to model the return of the nozzle liner and flap cooling flows in mixed flow, augmented engines. When these nozzle cooling ducts exist they are assumed to always remain open for passing flow whether or not the augmentor is turned on.

DEFINITIONS OF ENGINE EFFICIENCIES

DEFINITIONS OF ENGINE EFFICIENCIES: Some of the performance outputs from TRBOFN are engine efficiencies and thrust specific fuel consumption. Their definitions and methods of calculation follow.

1. TSFC Definition: Thrust Specific Fuel Consumption (TSFC) is defined as the rate at which fuel is being burned divided by the amount of thrust being produced as a result. That is:

$$TSFC = \dot{m}_f / F_n$$

The units on TSFC are pounds of fuel per hour per pound of thrust.

2. Efficiency Definitions: Defining the engine efficiencies described below will help show the dependence of TSFC on how efficiently the engine uses the energy released by the burning of fuel.

Thermal Efficiency: Thermal efficiency is a measure of how well the core of the engine makes use of the energy made available by burning fuel. Only some of the air acted upon by the fan goes through the core of the engine. The rest goes through the bypass duct (Figure 11).

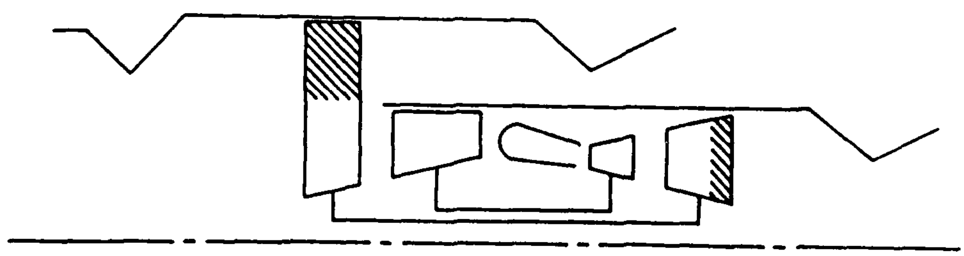


Figure 11. Part of the Low Pressure Turbine Drives the Part of the Fan that Acts on the Bypass Air

The work required to drive only the portion of the fan that acts on the air that goes through the core of the engine is a fraction of the total work extracted by the low pressure turbine. We can think of this as being done by a turbine that is only a fraction as large as the original turbine which was required to extract a sufficient amount of work to drive the entire fan. Consider the engine with these two "partial" components in it (Figure 12).

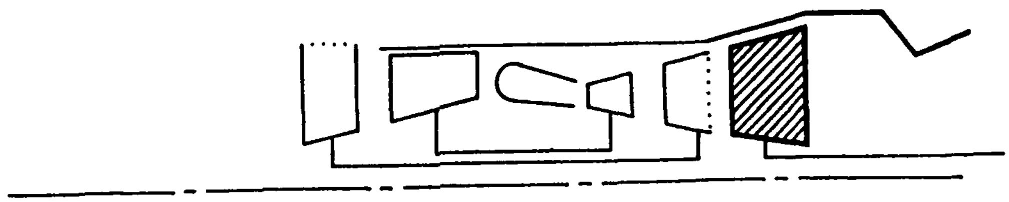


Figure 12. Partial Components for Thermal Efficiency Calculation

Thermal efficiency is defined as the amount of energy available to do useful work that remains in the core airstream after a sufficient amount of work has been drawn from the stream by the portion of the low pressure turbine needed to drive the part of the fan which acts only on the air that goes through the core of the engine. The way to calculate the rate at which energy is made available to do useful work is to calculate the rate at which energy can be extracted from the stream with an ideal turbine, i.e. a turbine with a component efficiency of unity while leaving a sufficient amount of energy to produce zero net thrust on the system after perfect expansion through a nozzle. This device is represented in Figure 12 as the large cross-hatched turbine labeled IT1 (Ideal Turbine 1). The zero thrust requirement in the definition makes thermal efficiency independent of the flight velocity. The rate at which energy is released by the burning fuel is calculated as the product of the mass flow of the fuel and the fuel lower heating value. The fuel lower heating value is the amount of energy released per mass of fuel burned. Its units are Btu per pound mass.

Transfer Efficiency: Transfer efficiency is a measure of how efficiently energy is transferred from the low pressure turbine to the bypass stream. It is defined as the total energy in both the core and bypass streams available to do useful work after the low pressure turbine has drawn off enough energy to drive the entire fan divided by the work drawn off by the ideal turbine described in the thermal efficiency definition. Referring to Figure 13, the numerator is calculated as the sum of the work extracted by two ideal turbines; one in the core stream, IT2, and the other in the bypass stream, IT3. The energy extracted by each of these turbines is determined such that the exit streams each produce zero net thrust after perfect expansion through a nozzle. The denominator is the work extracted by IT1 in Figure 12. That is:

$$\eta_{tr} = \frac{\dot{W}_2 + \dot{W}_3}{\dot{W}_1}$$

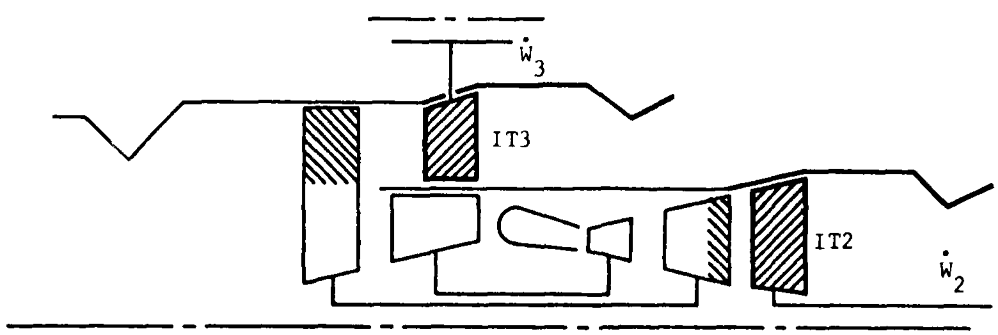


Figure 13. Ideal Work Extraction for Transfer Efficiency Calculation

<u>Propulsive Efficiency:</u> Propulsive efficiency is a measure of how well energy available is converted to thrust power. It is calculated as the fraction of the total energy available to do useful work in both exhaust streams that shows up as actual thrust work. The total energy in the exhaust streams is the sum of the work extracted by the two ideal turbines used in the transfer efficiency definition, IT2 and IT3 in Figure 13. Thrust power is simply the thrust (force) times the flight velocity. That is:

$$\eta_{pr} = \frac{F_n u_o}{\dot{W}_2 + \dot{W}_3}$$

THE DESIGN PROCESS

THE DESIGN PROCESS: You should find it easy to follow the design process for both mixed and separate flow engines in detail by reading the comments and FORTRAN code that make up subroutine DESIGN. The preceding explanations of the basis and workings of the component models should make each of them very easy to understand when reading the code and comments that make them up.

OFF-DESIGN OPERATION

OFF-DESIGN OPERATION: Off-design operation of a turbofan engine includes throttled power settings and intermediate power settings at other-than-design flight conditions. Calculating off-design performance for a turbofan engine is considerably more complicated than calculating design performance because balanced off-design engine performance can't be calculated analytically with the assumptions we used to generate this model. We chose to use a "nested DO loop" approach in iterating to find balanced off-design operating points. Several other approaches have been used in other engine performance simulation programs, most of which require less programming steps and run faster, but we have found them terribly difficult to understand with the poor documentation available with them. While the method of programming we chose requires more coding and results in longer run times, it also makes it possible to write an understandable program that you don't have to be the author of to understand and use. We authors were willing to sacrifice running speed to write an easy-to-use program that users could understand. We followed a comprehensive set of documentation standards in writing every part of the system of which TRBOFN is a part. Because of the extensive documentation in the programming itself, we believe that all the subroutines that make up this system should be easy to understand just by reading the "Purpose statement" and the comment lines throughout the coding.

1. Throttling: Balanced throttled power settings are found by the subroutine THROTL. THROTL incrementally increases the burner dilution fraction to simulate throttled power settings. It then calls TRBOFN's workhorse subroutine, BALENG, which gets its name from what it does: BALance the ENGine. Balancing the engine refers to finding the set of engine cycle parameters that satisfy conservation of energy, momentum and massflow throughout the engine. BALENG sets initial guesses on several parameters it needs to get started and calls three other major controlling subroutines which are described below. You can see which parts of the engine each of these major control routines operates on by looking at Figure 14.

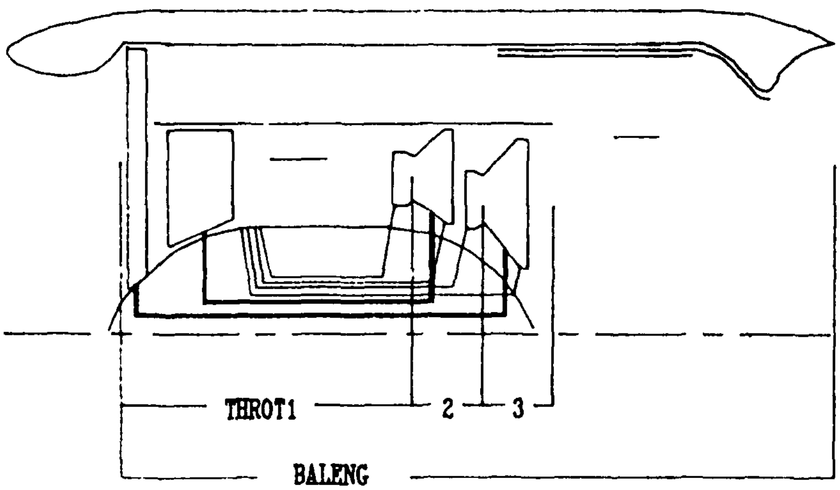


Figure 14a. Parts of Mixed Flow Engines Controlled by the Major Subroutines Called by BALENG

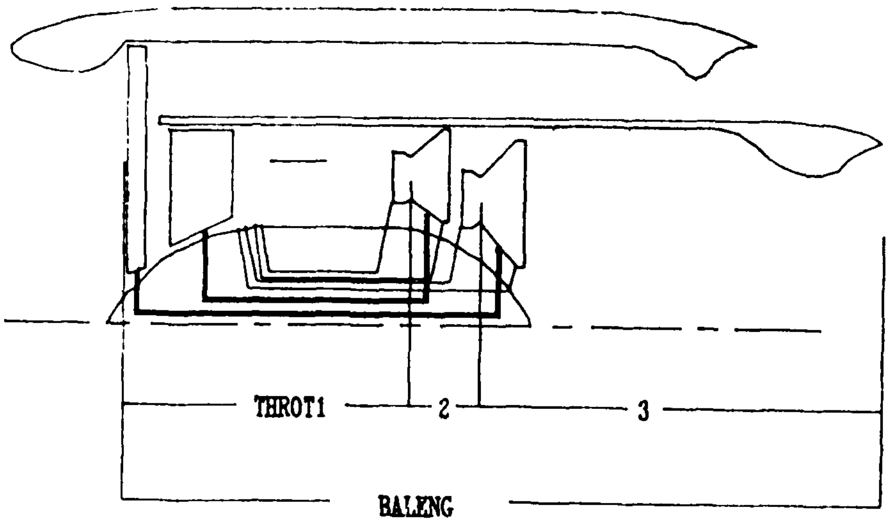


Figure 14b. Parts of Separate Flow Engines Controlled by the Major Subroutines Called by BALENG

THROT1 performs calculations using appropriate component models to ensure balanced operation of the engine between the compressor exit, station 31, and the choke point in the high pressure turbine's first stage vanes, station 41.

THROT2 iterates to find a balance between stations 41 and 47, the choke points in the high and low pressure turbines' first stage vanes. One resultant parameter from THROT2 is the work extracted from the flow by the high pressure turbine. BALENG uses this to iterate to balance the core of the engine. That is, BALENG changes the driving parameter in its core balance loop until the work extracted by the high pressure turbine balances with the work required to drive the compressor at the current compressor pressure ratio.

THROT3 is called each time the core balance loop is satisfied. Its job is to calculate the work extracted by the low pressure turbine and to do either of two other things, based on whether the engine design is mixed flow or separate:

For mixed flow designs: THROT3 iterates to find the appropriate low pressure turbine expansion ratio which results in the required static pressure balance for mixing the core exit stream at station 50 and the bypass stream at station 15.

For separate flow engines: THROT3 iterates to find the low pressure turbine expansion ratio which results in a choked core nozzle if the back pressure exerted by the atmosphere is sufficiently low to allow choking. If the pressure in the core duct relative to that in the atmosphere is insufficient to choke the nozzle, then THROT3 iterates to find the appropriate turbine expansion ratio that results in a perfectly expanded nozzle with exit area equal to the design choke area, A_{80}.

In either case, THROT3 returns the work extracted by the low pressure turbine to BALENG which uses this quantity to compare to the work required to drive the fan and adjusts the fan pressure ratio to match the work extracted by the turbine to get the fan pressure ratio for the next iteration. BALENG continues to iterate in this manner, each time through iterating to achieve a balanced core and adjusting fan pressure ratio based on the information THROT3 returns until the engine is balanced all the way through (i.e. the work out from the high pressure turbine matches the work required to run the compressor, an analogous situation is true for the fan spool, the first stage vanes of both turbines are choked and have the appropriate massflows going through them and the nozzle is choked and/or perfectly expanded).

2. Off-Design Flight Conditions: To find the intermediate power setting at an off-design flight condition, TRBOFN calls subroutine OFFDSG which calls BALENG to performs the functions described above under Throttling. Initial guesses for the iterative process that leads to finding the off-design flight condition's intermediate power setting are generated in subroutine INTGES (INiTial GuESs). OFFDSG (OFF DeSiGn) uses subroutine BEST05 (BEST Of 5) to get consecutive guesses on the burner dilution fraction (PMBDL) in its iteration to find the intermediate power setting. Once the intermediate power setting's PMBDL is known, finding throttled power settings at off-design flight conditions is done in exactly the same way as at the design flight condition.

a. The Intermediate Power Setting: The intermediate power setting at an off-design flight condition is defined as the state of balanced engine operation where one of the possible control parameters is at its control limit while all the others are below theirs.

b. The Possible Control Limits: There are five possible control limits which must be checked for each balanced state of engine operation (i.e., each balanced engine operating condition found by BALENG for each guess on PMBDL generated by BEST05 from OFFDSG). The five possible control limits are:

1) The physical rotational speed of the low pressure (fan) spool (PPN1) is calculated as a fraction of the design speed by subroutine OPPCN (OPerating Point Corrected N, where N is the spool speed in RPM). Its limiting value is 100% of the design speed.

2) The physical rotational speed of the high pressure (compressor) spool (PPN2) is calculated and treated exactly like the fan physical spool speed.

3) The corrected rotational speed of the low pressure spool (PCN1) is also calculated as a fraction of the design value by subroutine OPPCN. It too is limited to 100% of the design value.

4) The corrected rotational speed of the high pressure spool (PCN2) is calculated and treated exactly like the corrected speed of the fan spool.

5) The fifth possible control parameter is selected by the user during the design process as either:

a) T40G, the gas temperature entering the high pressure turbine's first stage vanes (Turbine Inlet Temperature),

b) or T40MVA, the high pressure turbine's first stage Vane Metal temperature Allowable.

The user also sets the design (limiting) value of this parameter during the design process.

c) BESTO5: Each time OFFDSG calls BESTO5, it projects a new guess on PMBDL for each of the five control parameters by assuming the variation of each control parameter is linear in PMBDL. These five linear projections result in five different values of PMBDL, each of which would put one of the control parameters at its limiting value if the parameter's value really varied linearly with PMBDL. The intermediate power setting is defined as the point of balanced engine operation where only one of the control parameters is <u>AT</u> its limit while all the others are <u>BELOW</u> theirs. BESTO5, therefore, returns only the highest value of PMBDL of the five it calculates to be used as the next guess to be used in BALENG. It chooses the highest value of PMBDL because PMBDL is the percent of the total burner air used for dilution and a higher value of PMBDL means less fuel is being burned. When more fuel is burned, the engine runs hotter and faster. Setting PMBDL at one of the lower values calculated by BESTO5 would result in at least one control parameter having a value larger than its limiting value and therefore would not correspond to the intermediate power setting.

SUBROUTINE GROUPS

ALPHABETICAL LIST OF SUBROUTINES BY GROUPS:

	Gas Model	Comp Model	Control	Utility	Performance
AFBRNR		X			
ATMOS	X				
BALENG			X		
BESTO5				X	
CMP...		X			
DESIGN			X		
DILUTE		X			
ETA					X
GASPAC					
LOADG1	X				
MFRACS	X				
THERMH	X			X	
THERMI	X			X	
THERMP	X			X	
IDLXIT				X	
INPUT				X	
INTGES				X	
LOADA1				X	
MIX...		X			
NEWGES				X	
NOZCON		X			
OFFDSG			X		
OPPCN				X	
OUT...				X	
PDROP		X		X	
RAM			X		
RAMREC		X			
SETEQ				X	
STAT...				X	
STOICH		X			
THROT...			X		
THRUST					X
TRBOFN*			X		
TURB...		X			

* TRBOFN is the name of the mainline program

Chapter 4.

ENCOM: The Engine Sizing and Comparison Program

1. <u>Introduction</u>: ENCOM is an interactive program using a question-answer format to get input information from the user. It can read engine performance data from up to five files generated by the program TRBOFN on each run. That means it can be used to compare up to five engines at a time or to generate a file to plot a trend with five points.

ENCOM has three basic functions:

1. SIZING: to determine the minimum size of each engine relative to the others for each to be able to meet or exceed each of up to five user input maneuver requirements,

2. COLLECTING DATA FOR PLOTS: to collect the requested data from each of the five engine performance data files so the user can make plots of any stored parameter versus any other, and

3. MISSION ANALYSIS: to calculate performance throughout and to ultimately determine the minimum fuel-to-take off gross weight fraction necessary for each engine to complete an eleven leg fighter/ground attack mission in the same fighter aircraft.

The purpose of this chapter is to tell you about what ENCOM can do. To find out exactly how ENCOM does all these things you'll have to read the documentation included in the actual FORTRAN source coding of the program. Like all the other programs in this system, ENCOM is made up of a mainline control code which calls several subroutines to perform specific functions. The mainline and every subroutine follow the same documentation standards: each includes a statement of purpose followed by an explanation of each variable passed into and out of the subroutine and at least one comment line for every line of FORTRAN coding throughout the program.

SIZING:

The sizing process in ENCOM requires several user inputs:

o up to five maneuver requirements (i.e., flight Mach number, altitude, sustained acceleration requirement, take-off wing loading and maneuver wing loading)

o which engine is to be used as the standard for comparison,

o the names of the data files created by TRBOFN to be read by ENCOM to get the engine performance information needed to size the engines relative to each other. NOTE: All engine performance data files to be used by ENCOM must have sea level static performance information .

Once one engine is selected as the standard for comparison, the other engines' sizes are scaled up or down relative to that engine's so that their thrust output at each maneuver requirement is sufficient to propel the aircraft through the specified maneuver. This results in a sizing factor beign calculated for each engine relative to the standard for each maneuver requirement. It also enables ENCOM to calculate the sea level static thrust-to-weight ratio for the airplane with each engine scaled by each sizing factor. The critical maneuver requirement is the one that forces the airplane to have the highest sea level static thrust-to-weight ratio. That maneuver requires the engine to be scaled up the most. If the engine is scaled to meet the critical maneuver requirement, then it will be more than big enough to complete the other maneuver requirements. Once the critical maneuver requirement is determined for each engine, the corresponding sizing factor is used to calculate that engine's physical size, total airflow size and core airflow size relative to the standard's.

COLLECTING DATA FOR PLOTS:

Subroutine PLOTCON is called by ENCOM to control the collection of data for plots. PLOTCON uses other subroutines to perform parts of the collection functions. For instance, WHAT2PLOT is the subroutine that displays the choices for parameters in the engine performance data files that PLOTCON can get and output in the proper form for use by GRAPH. WHAT2PLOT also prompts the user to input his choices for the parameter he wants on each exis of the graph. The parameters are displayed as a table of rows and columns and the user specifies which parameter he wants by entering its row and column location on the table. PLOTCON then uses other subroutines to get the user to tell it whether he wants throttling trends plotted for each engine or just intermediate power points, augmented performance, or dry power only, one flight condition or a series, etc. Once PLOTCON knows enough about what the user wants it to get from the engine performance data files, it calls COLLECT... subroutines to do the data collection. The COLLECT... subroutines return the data requested by the user to PLOTCON in arrays which are then written to a user-named output file by subroutine WRITOUT.

AD-A140 781 TURBOFAN ENGINE TECHNOLOGY EVALUATION SYSTEM USER'S GUIDE(U) FRANK J SEILER RESEARCH LAB UNITED STATES AIR FORCE ACADEMY CO V J VILLHARD APR 84 FJSRL-TR-84-0002

2/2

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END

6-84

1.0 2.8 2.5 3.2 2.2 3.6 4.0 2.0 1.1 1.8 1.25 1.4 1.6

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

MISSION ANALYSIS:

ENCOM's last function is calculating and comparing the performance of up to five engines while propelling an airplane through an eleven leg fighter/ground attack mission. A schematic of the mission is shown in Figure 15 with a description of each leg of the mission. A sample mission output file also follows.

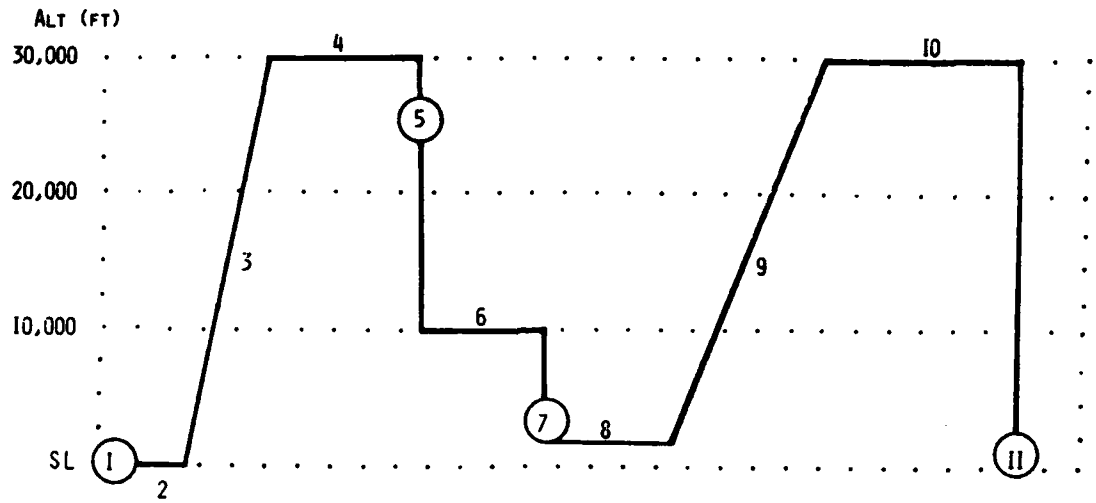


Figure 1. Schematic of Eleven Leg Fighter/Ground Attack Mission

LEG	Altitude (ft)	Flight Mach	Distance (n mi)	Time (min)
1 Warm Up	SL	static	-	15
2 Takeoff	SL	calc M_{to}	calc	calc
3 Climb & Accel	SL to 30K	0 to .88	calc	calc
4 Outbound Cruise	30K	.88	275	32
5 Loiter	25K	.54	sust 1.5 g turns	10
6 Dash & Penetrat	10K	1.10	150	13
7 Combat	2K	.93	2 360 deg turns	calc for 3g
8 Return Dash	2K	1.12	100	8
9 Climb & Decel	2K to 30K	1.12 to .88	calc	calc
10 Inbound Cruise	30K	.88	325	37
11 Landing Reserve	1K	.19	-	20

REFERENCES

1. Keenan, Chao, and Kaye, Gas Tables, Wiley, New York, 1980.

2. John, J.E., Gas Dynamics, Allyn and Bacon, Boston, 1977.

3. Andrews, F.C., Equilibrium Statistical Mechanics, Wiley, New York, 1975.

4. Mayer and Mayer, Statistical Mechanics, Wiley, New York, 1977.

5. Rosen, B. (ed), Selected Constants, Spectroscopic Data Relative to Diatomic Molecules, (in Spanish), 1970.

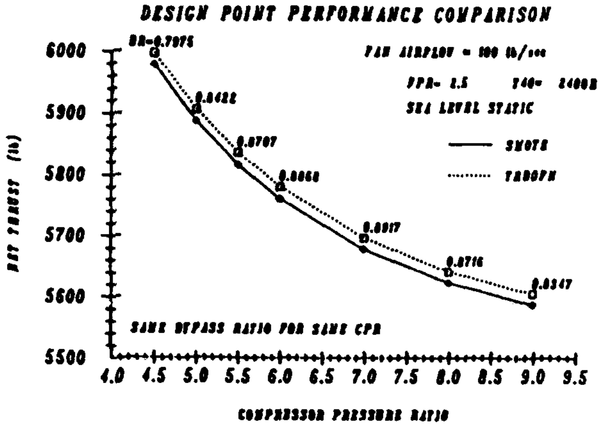
APPENDIX

Design Point Performance Comparison

In order to verify the accuracy of the performance calculated by TRBOFN, we decided to compare its outputs to an accepted standard turbofan engine performance simulation program currently in use at the Aero-Propulsion Lab at Wright-Patterson Air Force Base, Ohio: SMOTE.

This section of the Appendix shows how the performance calculated by TRBOFN compares to that calculated by SMOTE at the design point for over 200 engine designs. We chose to show the comparison between net thrust and thrust specific fuel consumption (TSFC) at the design point for each of these mixed flow turbofan engines.

Each graph in this section shows either thrust or TSFC information for each of six turbofan engine designs, all with the same fan pressure ratio (FPR) and turbine inlet temperature (T40), and with compressor pressure ratio (CPR) between 4.5 and 9.0. The designs compared include T40s of 2400 R, 2600 R, and 2800 R. Four different design flight conditions are included in this section: sea level static, Mach 0.7 at 15,000 ft altitude, Mach 0.9 at 15,000 ft, and Mach 0.9 at the tropopause, 36,089 ft. All the graphs show better than 4% agreement for every engine.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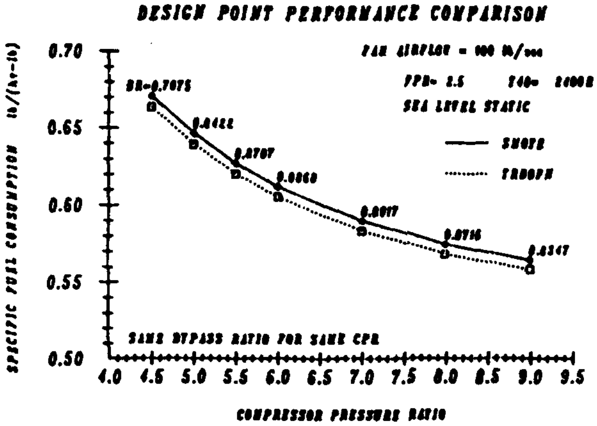
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
6000
5900
5800
5700
5600
5500
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO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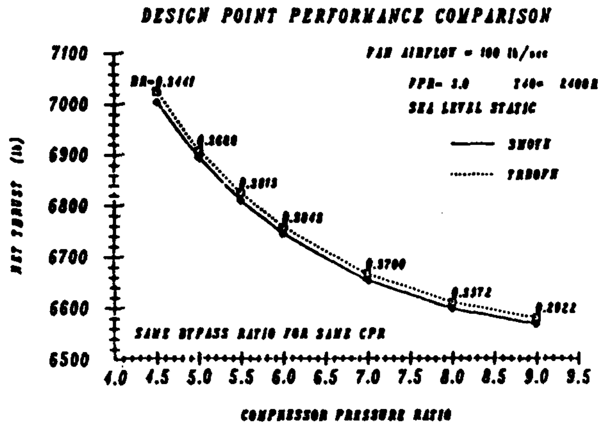
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
0.70
0.65
0.60
0.55
0.50
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO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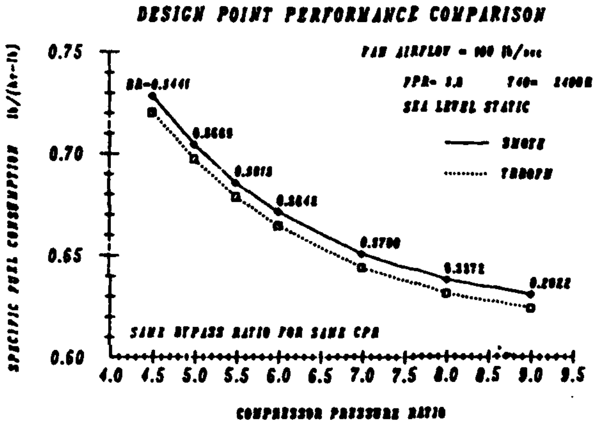
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
7100
7000
6900
6800
6700
6600
6500
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO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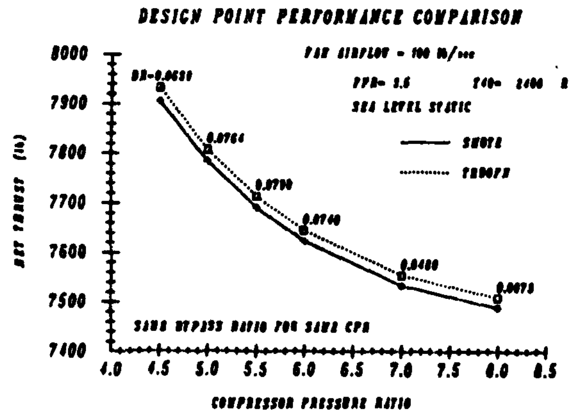
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
0.75
0.70
0.65
0.60
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO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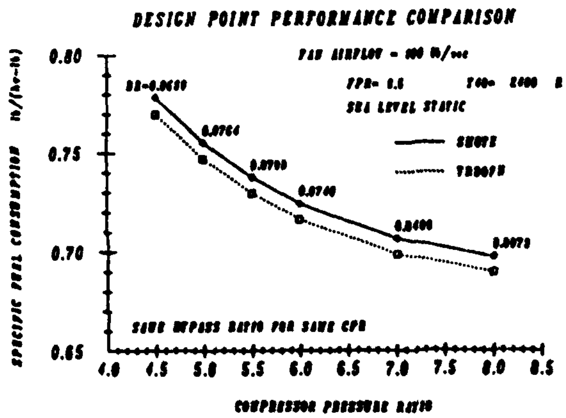
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
8000
7900
7800
7700
7600
7500
7400
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
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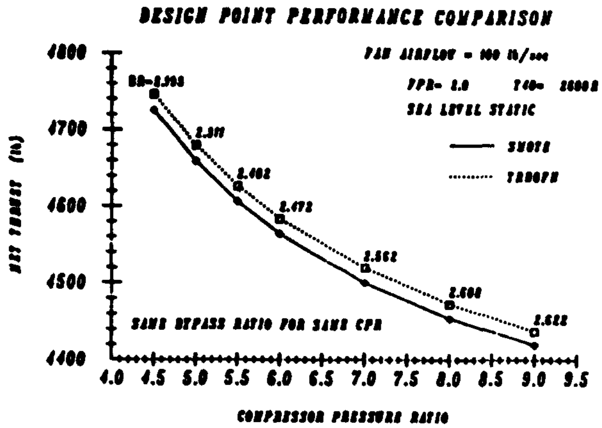
0.70
0.65
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5
COMPRESSOR PRESSURE RATIO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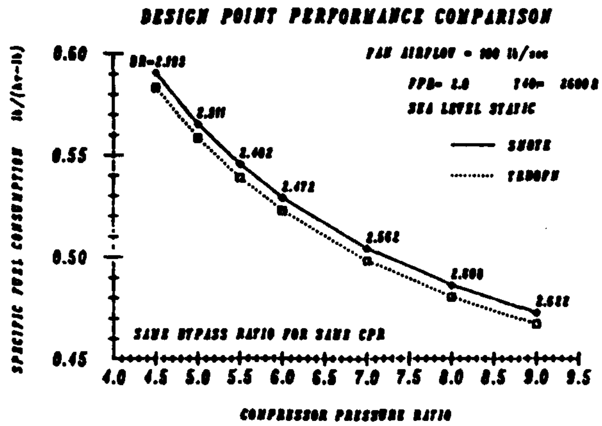
SEA LEVEL STATIC
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO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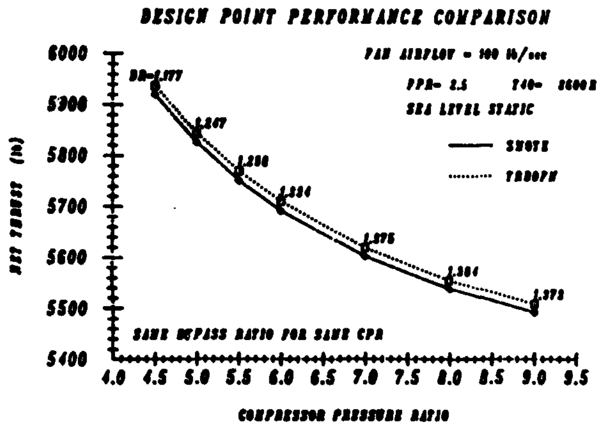
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO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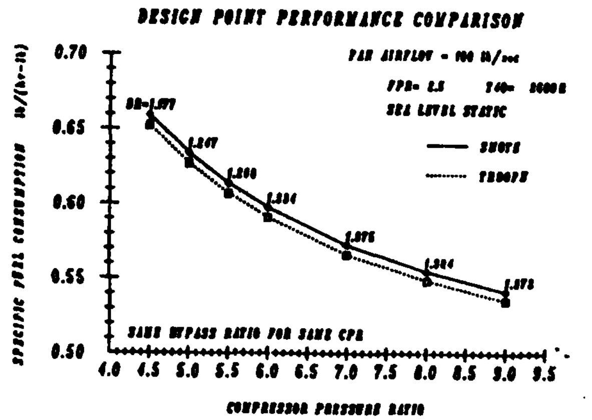
SEA LEVEL STATIC
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO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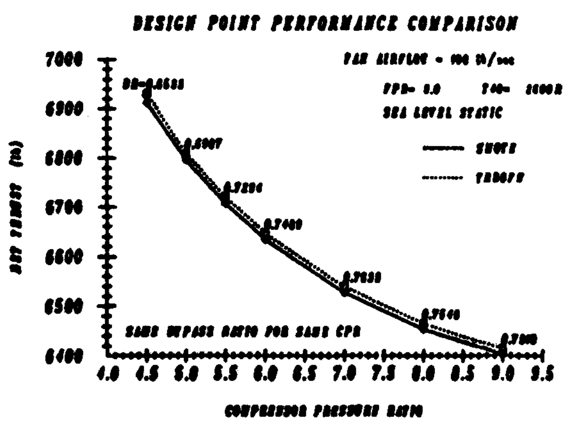
FPR= 2.5 T40= 2600R
SEA LEVEL STATIC
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO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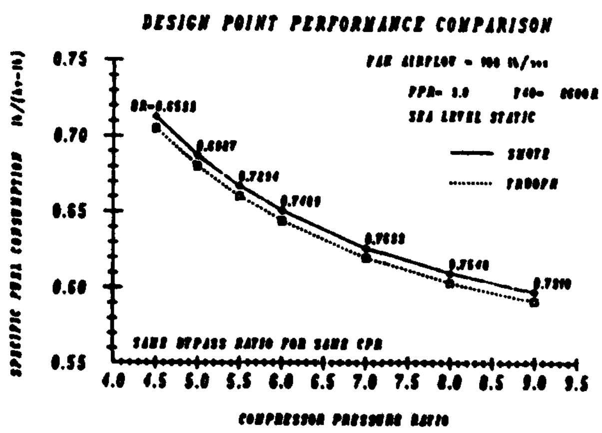
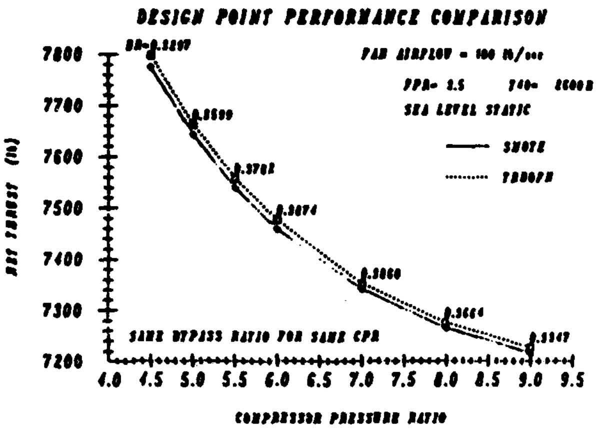
FPR= 3.0 T40= 2600R
SEA LEVEL STATIC
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 T40= 2600R
SEA LEVEL STATIC
SNOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO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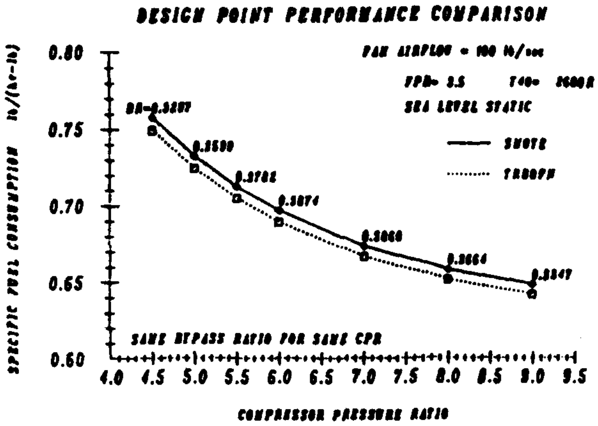
SEA LEVEL STATIC
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO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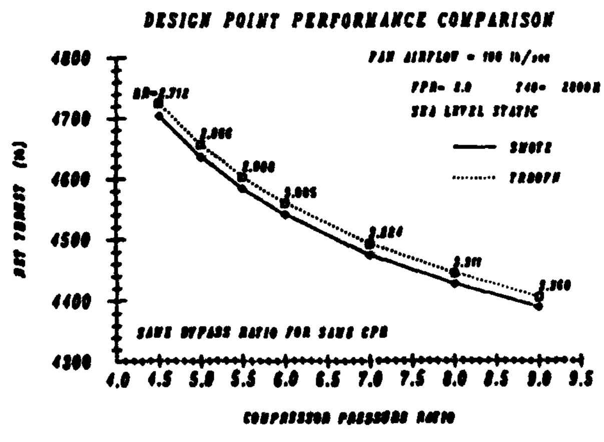
SEA LEVEL STATIC
SPECIFIC FUEL CONSUMPTION
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO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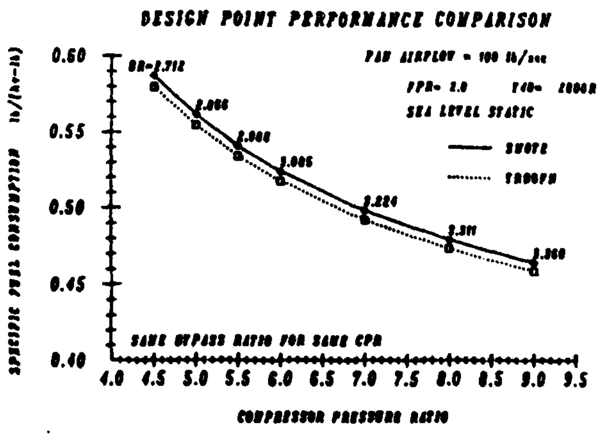
SEA LEVEL STATIC
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO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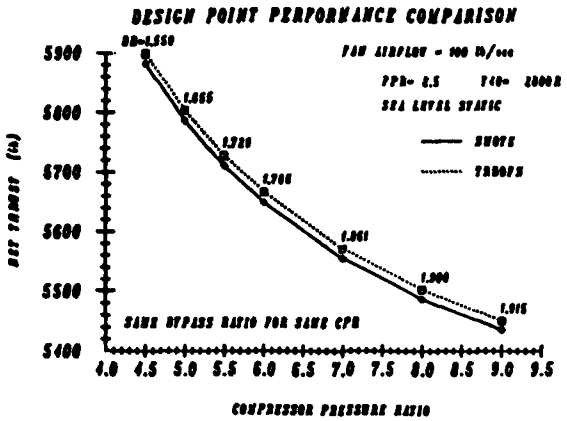
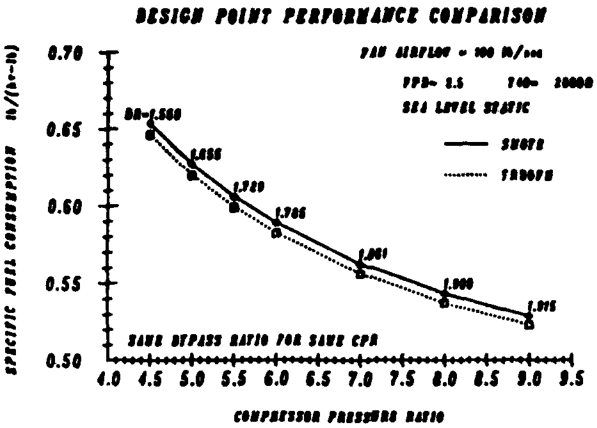
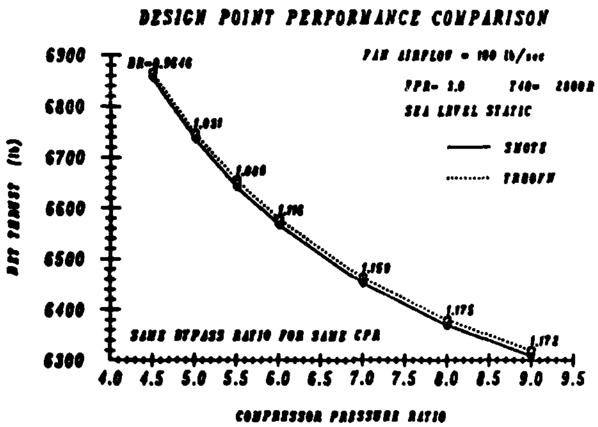
SPECIFIC FUEL CONSUMPTION
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
5900
5800
5700
5600
5500
5400
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(lb-h)
COMPRESSOR PRESSURE RATIO
0.70
0.65
0.60
0.55
0.50
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5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SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
6900
6800
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6500
6400
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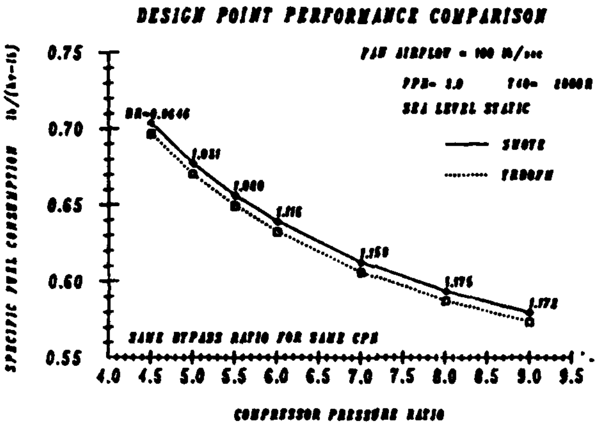
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SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(lb-h)
COMPRESSOR PRESSURE RATIO
0.75
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0.65
0.60
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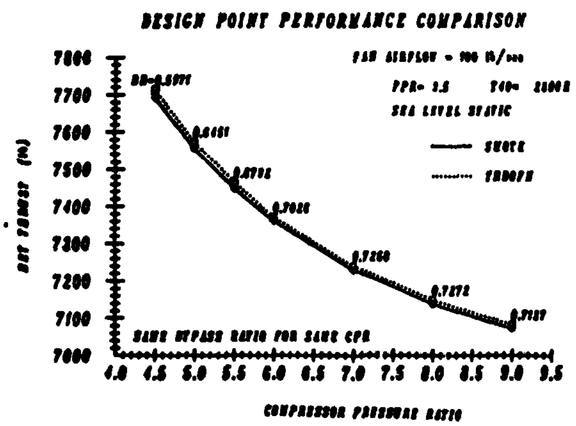
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SEA LEVEL STATIC
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
7800
7700
7600
7500
7400
7300
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7000
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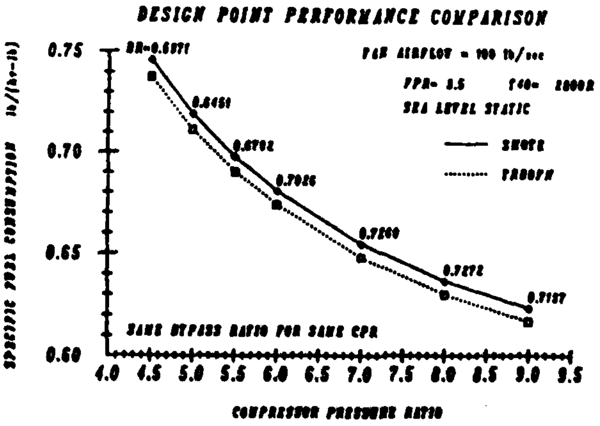
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SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(lb-h)
COMPRESSOR PRESSURE RATIO
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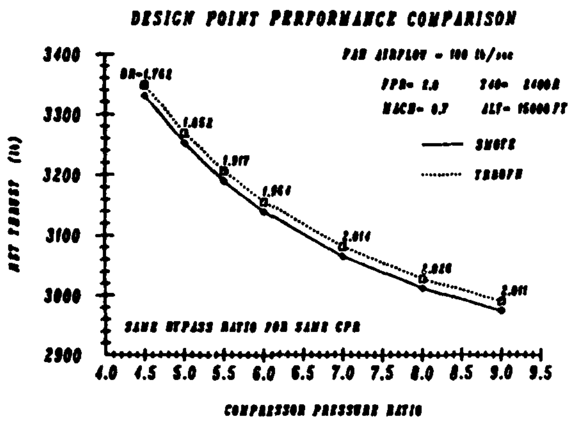
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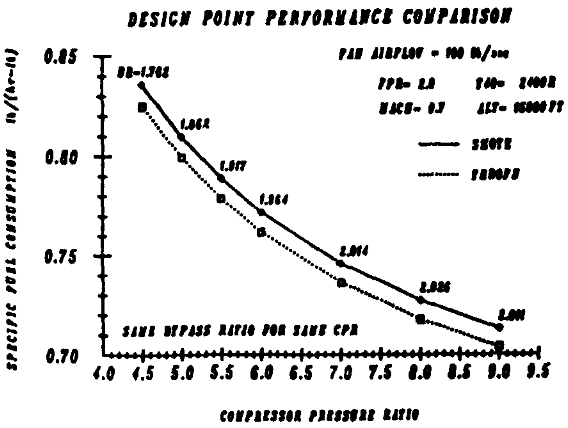
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO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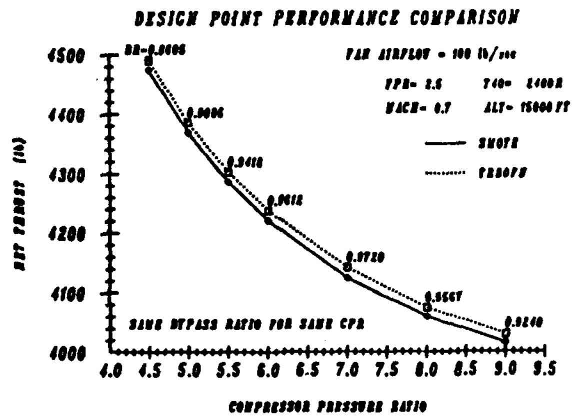
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO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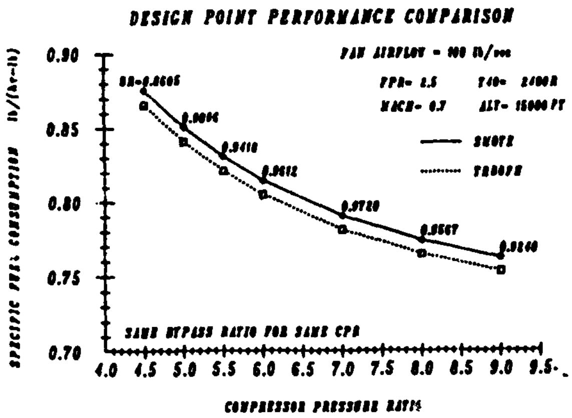
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO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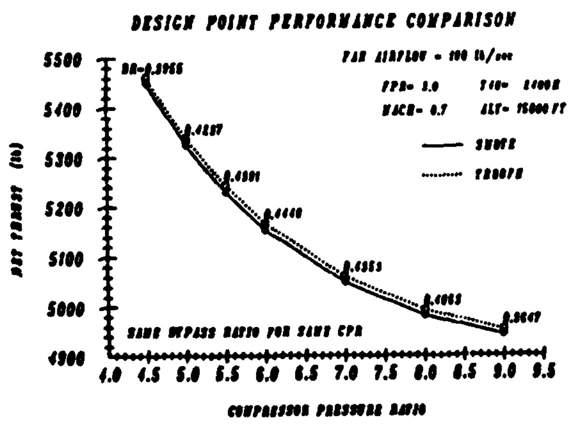
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO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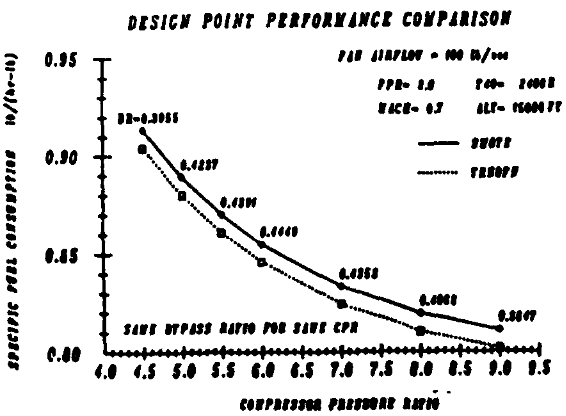
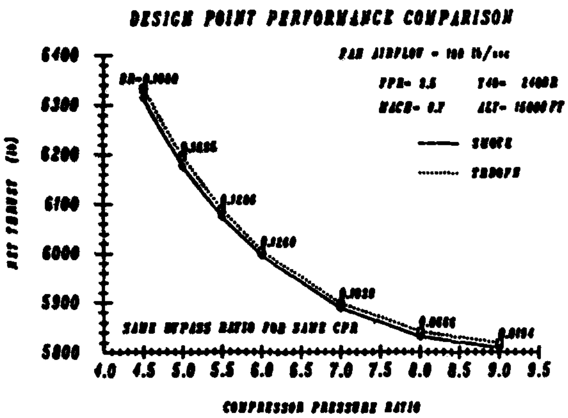
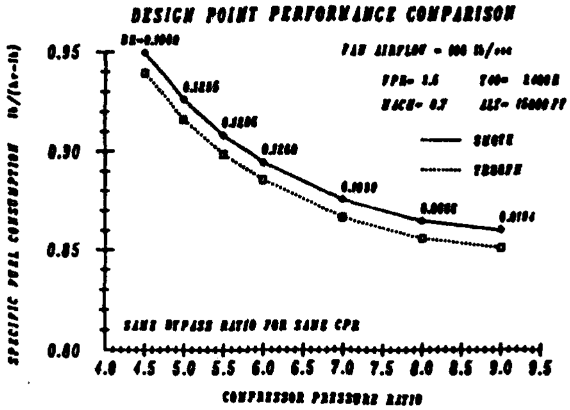
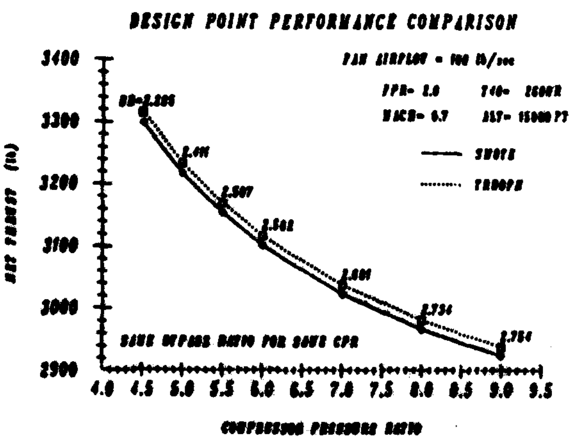
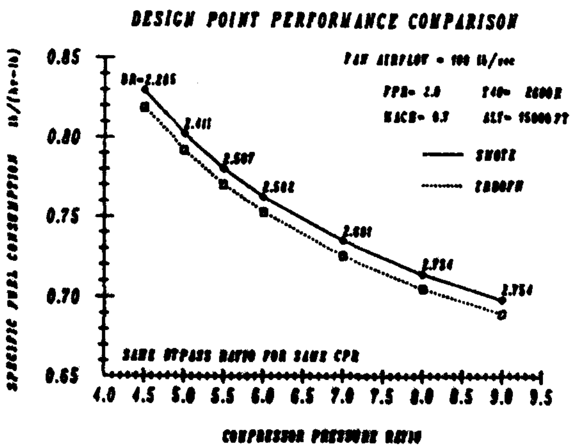
SHOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 T40= 2400R
MACH= 0.7 ALT= 15000 FT
SHOTE
TRBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO

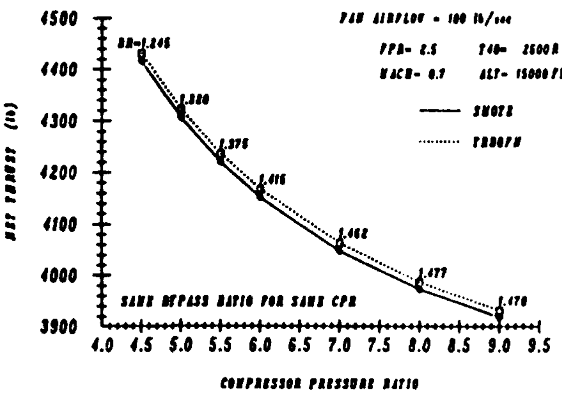

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
6400
6300
6200
6100
6000
5900
5800
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
0.95
0.90
0.85
0.80
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

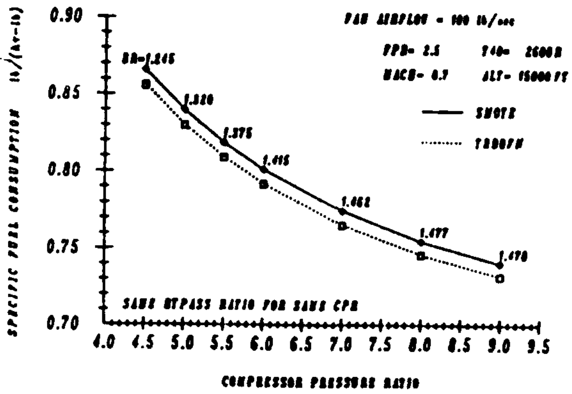

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
3400
3300
3200
3100
3000
2900
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
0.85
0.80
0.75
0.70
0.65
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

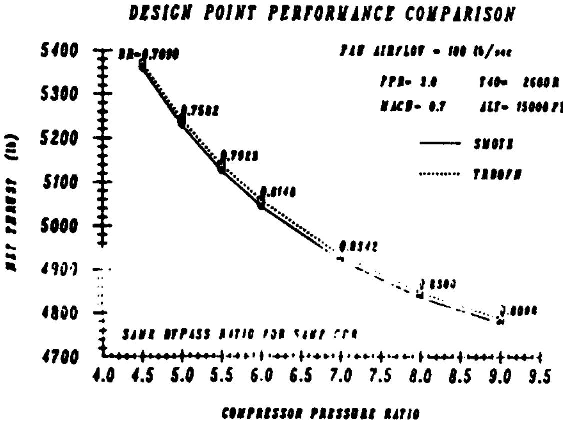
DESIGN POINT PERFORMANCE COMPARISON



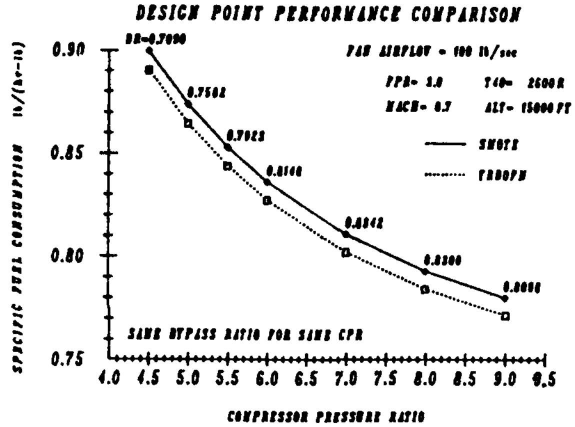
DESIGN POINT PERFORMANCE COMPARISON



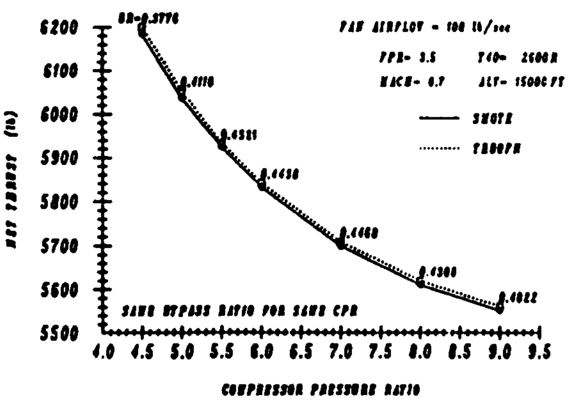
DESIGN POINT PERFORMANCE COMPARISON



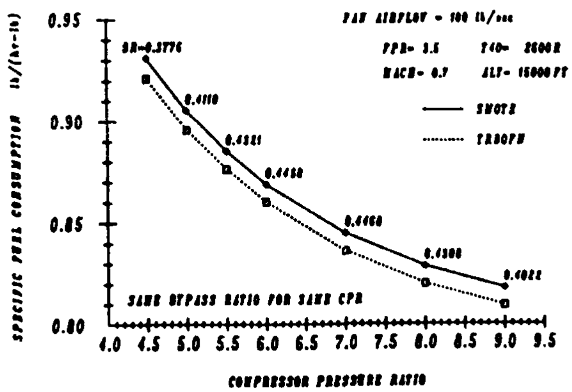
DESIGN POINT PERFORMANCE COMPARISON

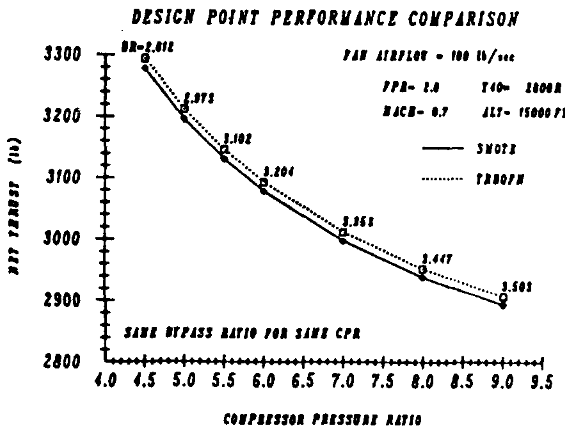


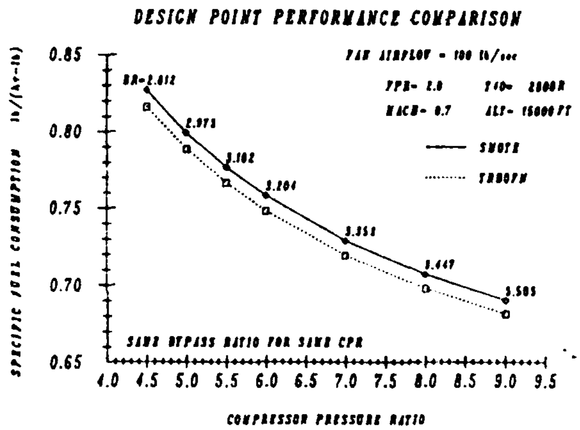
DESIGN POINT PERFORMANCE COMPARISON

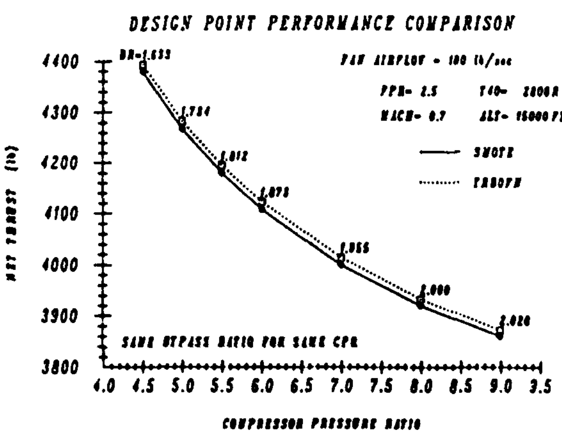


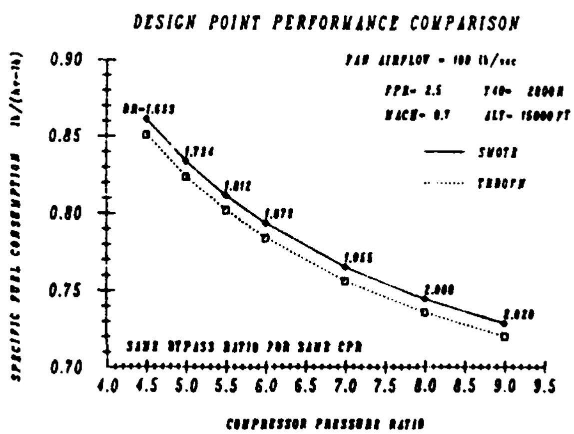
DESIGN POINT PERFORMANCE COMPARISON



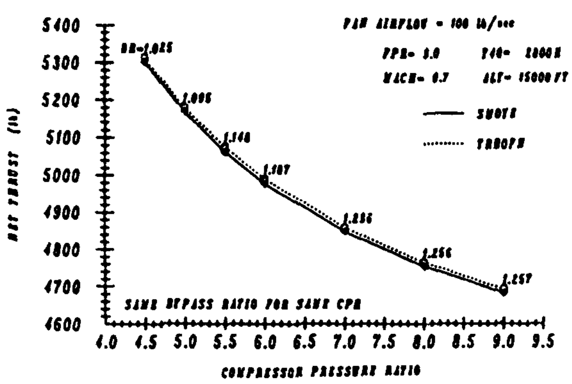

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
3300
3200
3100
3000
2900
2800
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
0.85
0.80
0.75
0.70
0.65
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

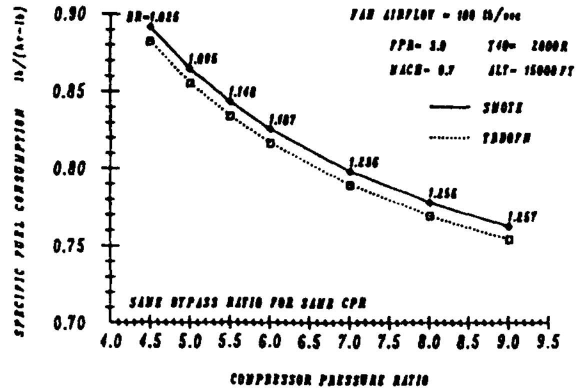

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
4400
4300
4200
4100
4000
3900
3800
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
0.90
0.85
0.80
0.75
0.70
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

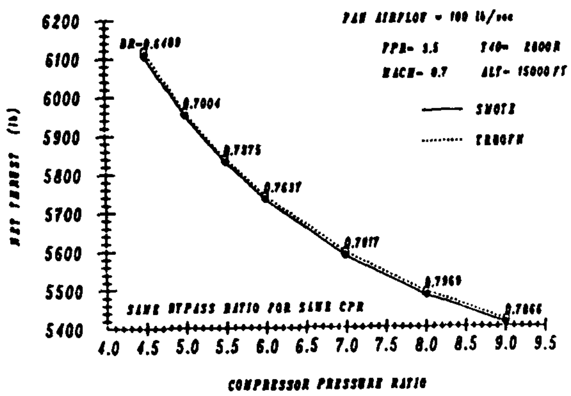
DESIGN POINT PERFORMANCE COMPARISON



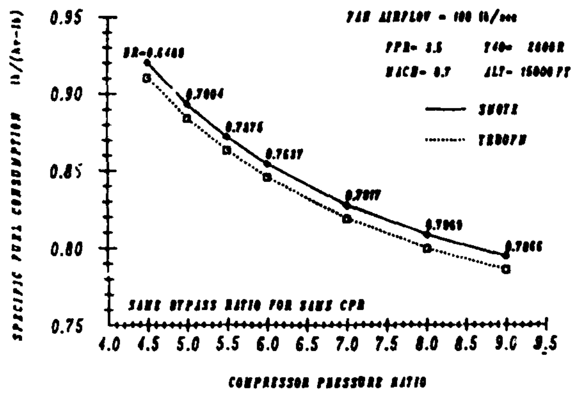
DESIGN POINT PERFORMANCE COMPARISON

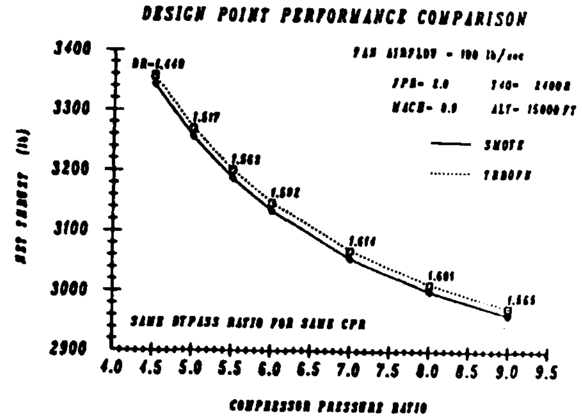


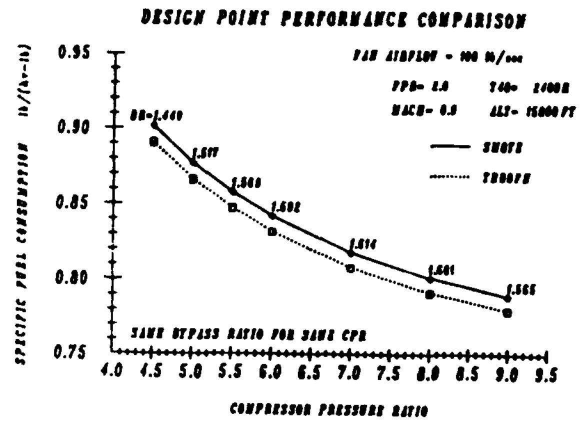
DESIGN P. T PERFORMANCE COMPARISON

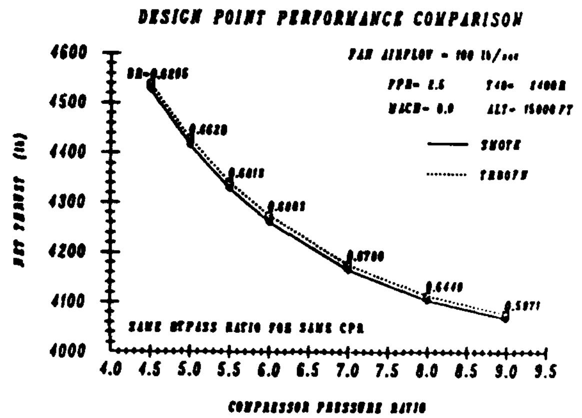


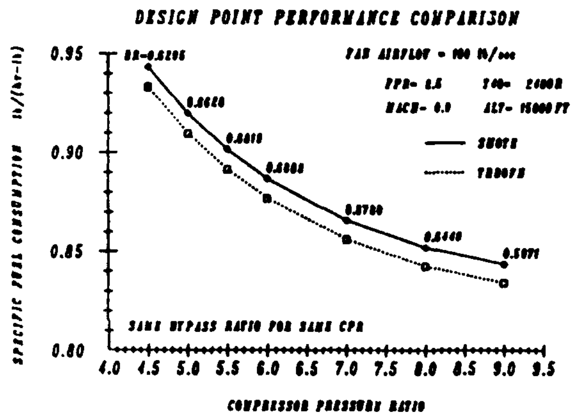
DESIGN POINT PERFORMANCE COMPARISON

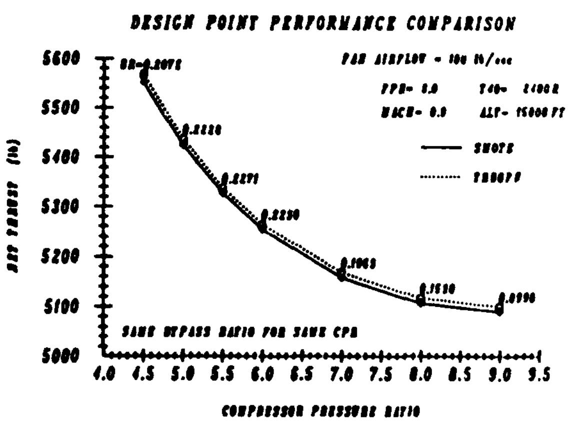


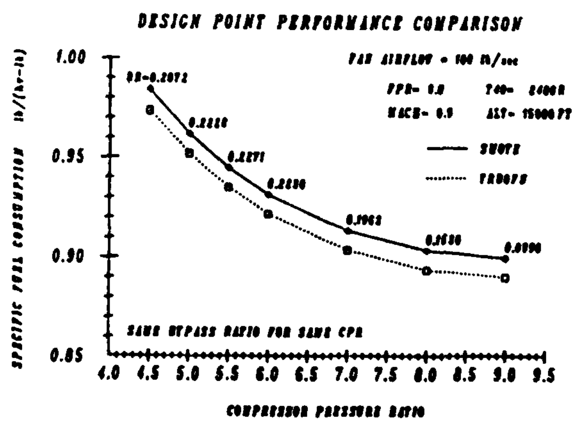

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SPECIFIC FUEL CONSUMPTION
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

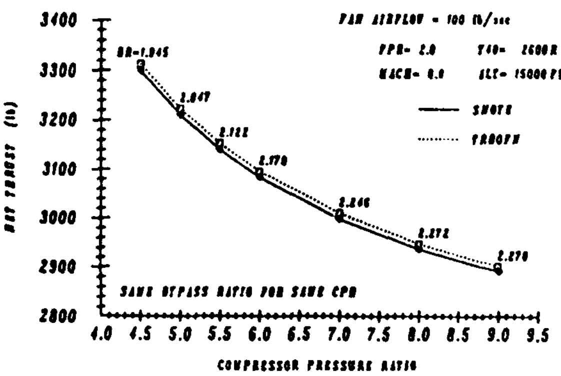

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SPECIFIC FUEL CONSUMPTION
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

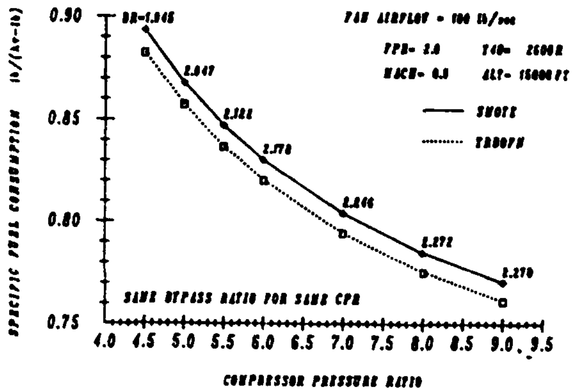

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO


DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SPECIFIC FUEL CONSUMPTION
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

DESIGN POINT PERFORMANCE COMPARISON



DESIGN POINT PERFORMANCE COMPARISON



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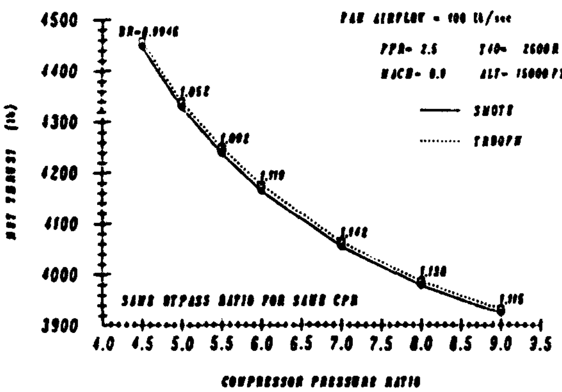
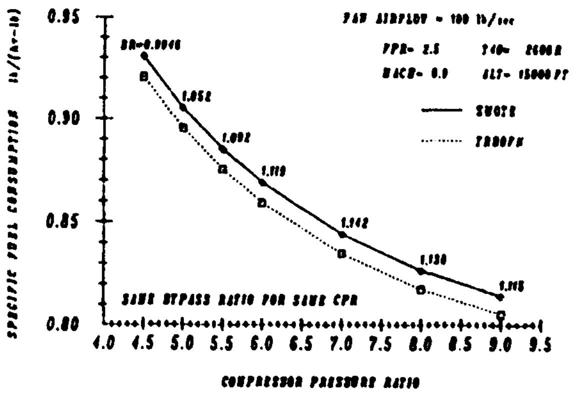
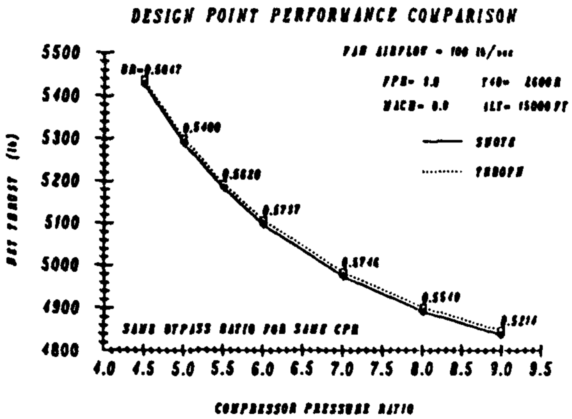
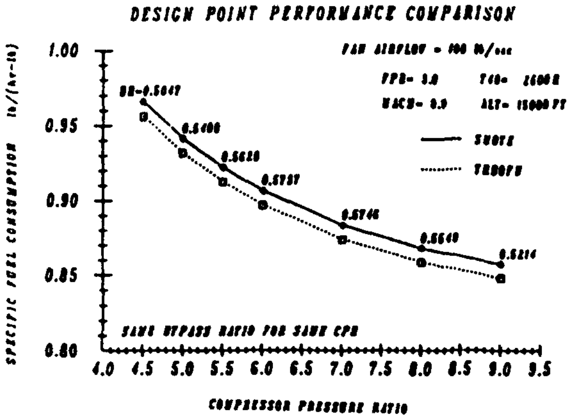
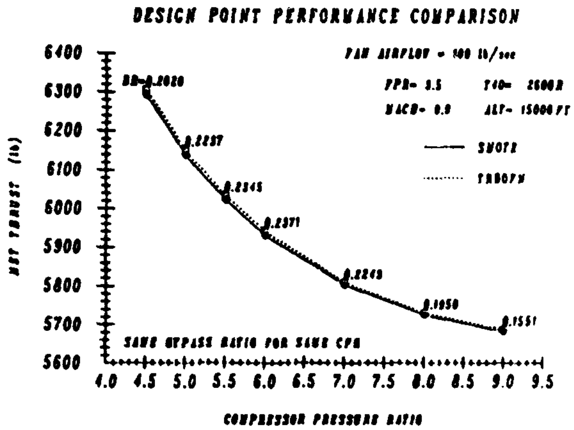


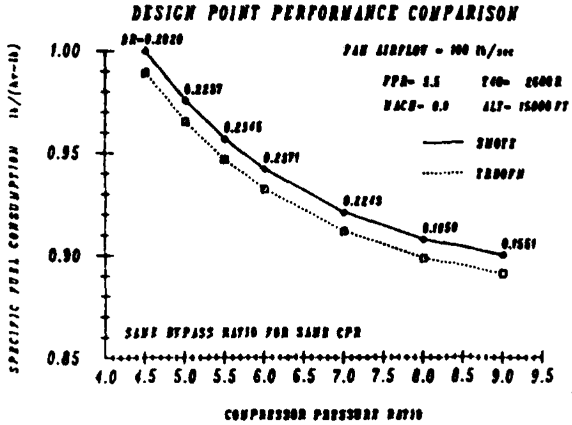
DESIGN POINT PERFORMANCE COMPARISON

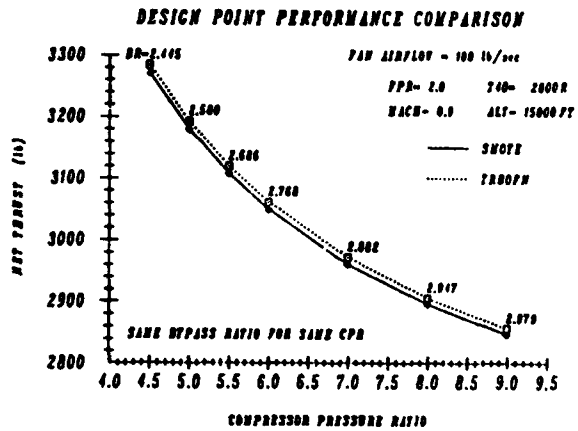


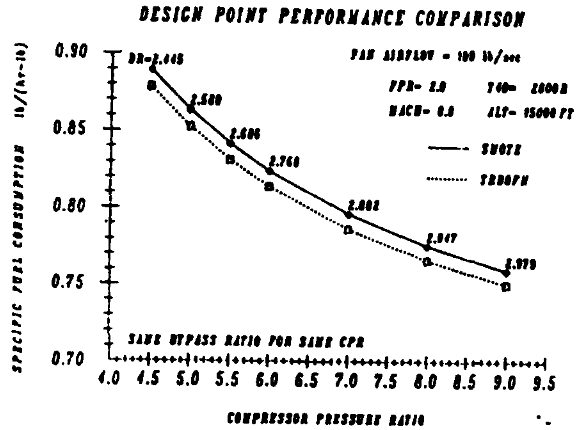

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SNOTE
TRBOFN

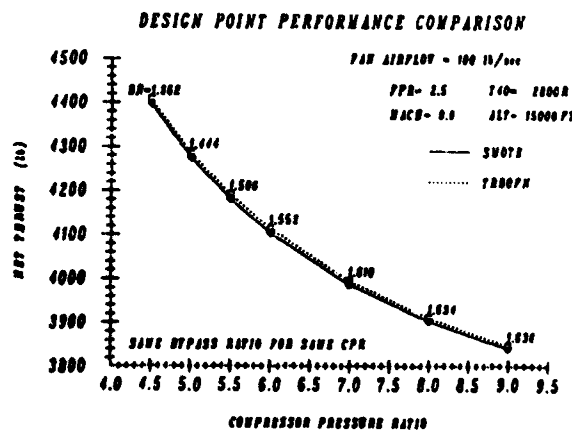

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SNOTE
TRBOFN

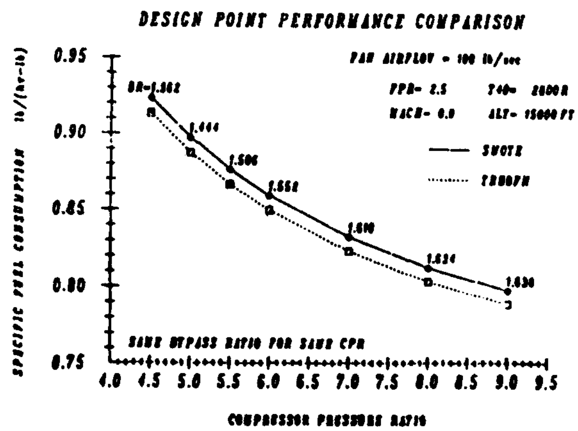

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SNOTE
TRBOFN

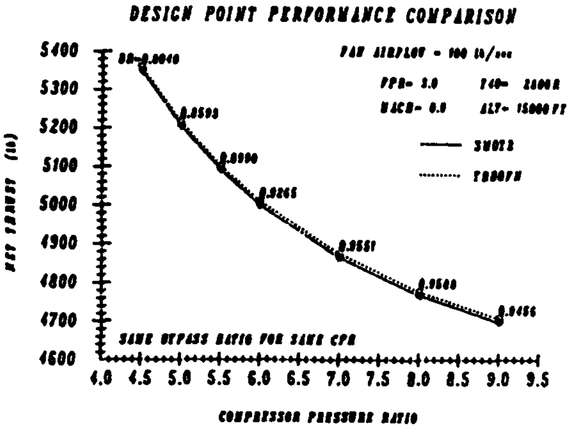

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SNOTE
TRBOFN

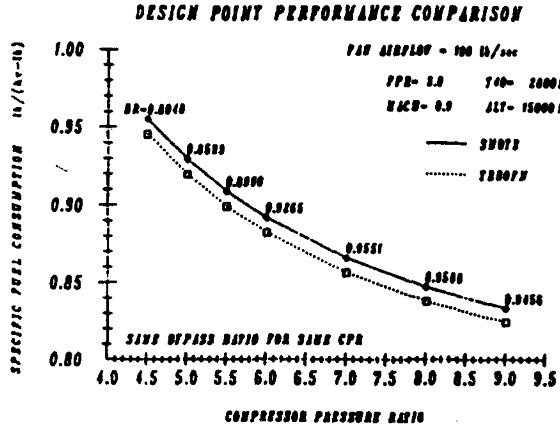

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

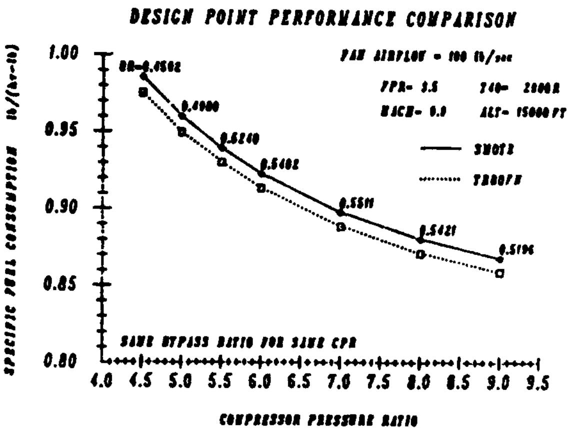

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

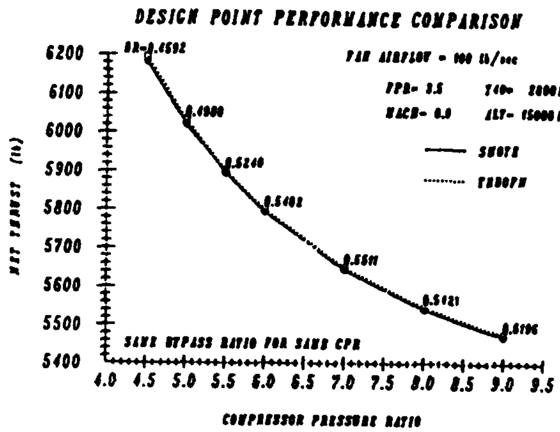

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

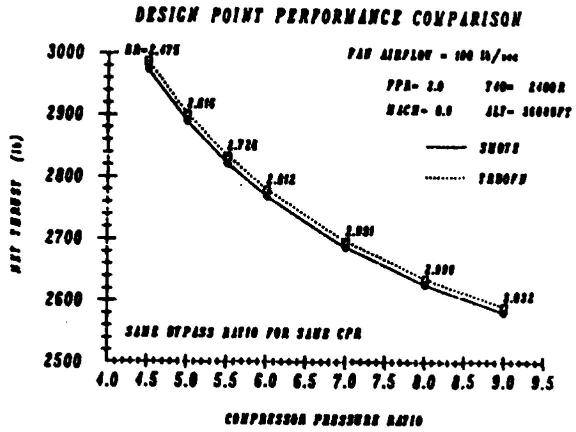

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

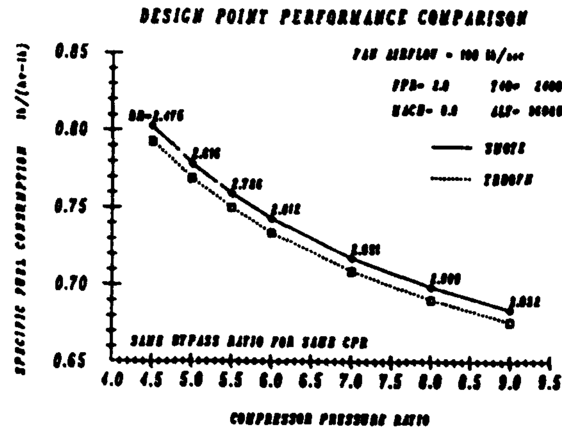

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
5400
5300
5200
5100
5000
4900
4800
4700
4600
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

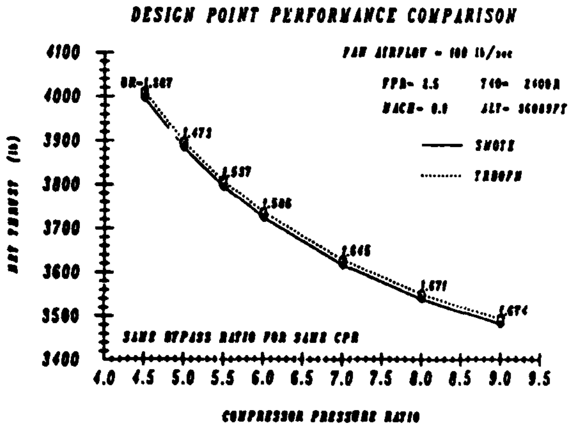

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
1.00
0.95
0.90
0.85
0.80
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

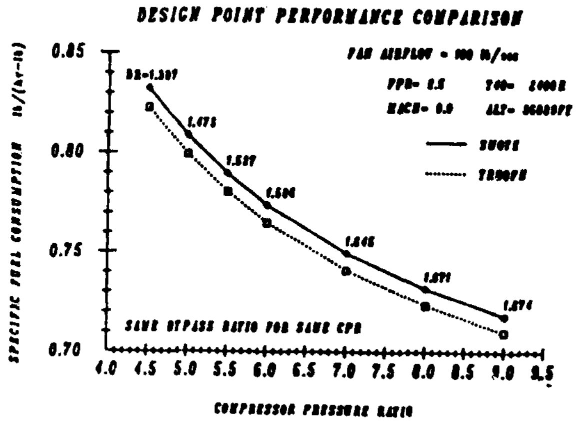

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
1.00
0.95
0.90
0.85
0.80
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

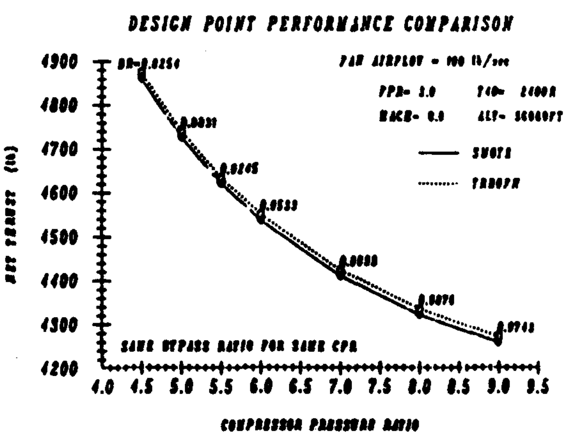

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
6200
6100
6000
5900
5800
5700
5600
5500
5400
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

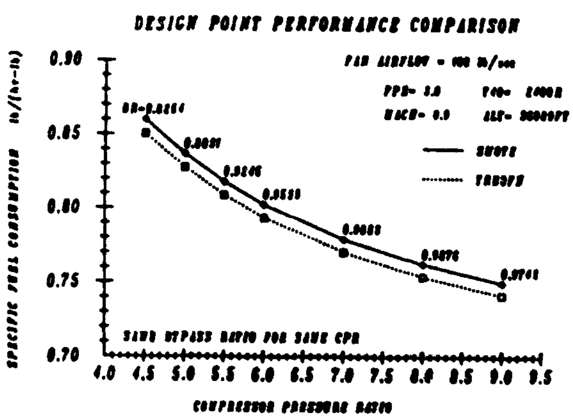

DESIGN POINT PERFORMANCE COMPARISON
3000
2900
2800
2700
2600
2500
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

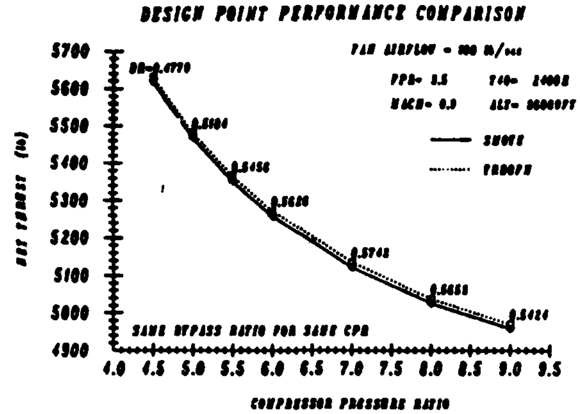

DESIGN POINT PERFORMANCE COMPARISON
0.85
0.80
0.75
0.70
0.65
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

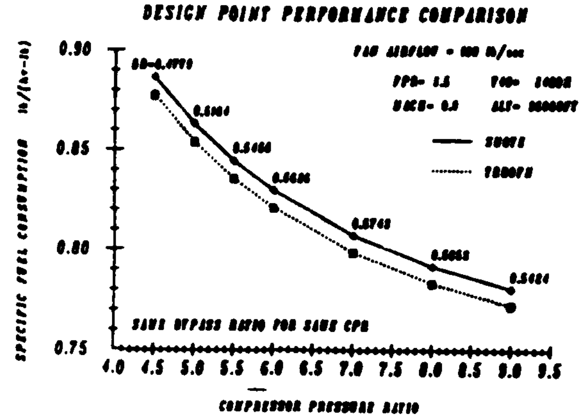

DESIGN POINT PERFORMANCE COMPARISON
4100
4000
3900
3800
3700
3600
3500
3400
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

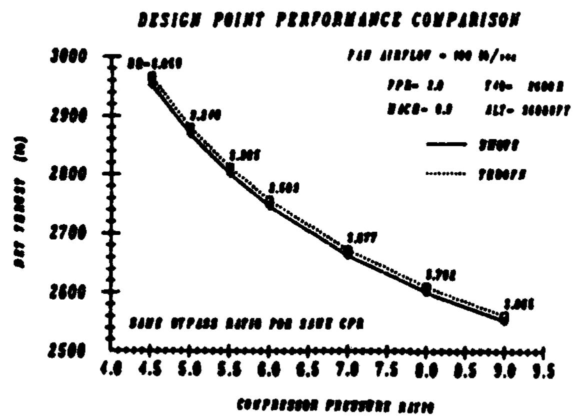

DESIGN POINT PERFORMANCE COMPARISON
0.85
0.80
0.75
0.70
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

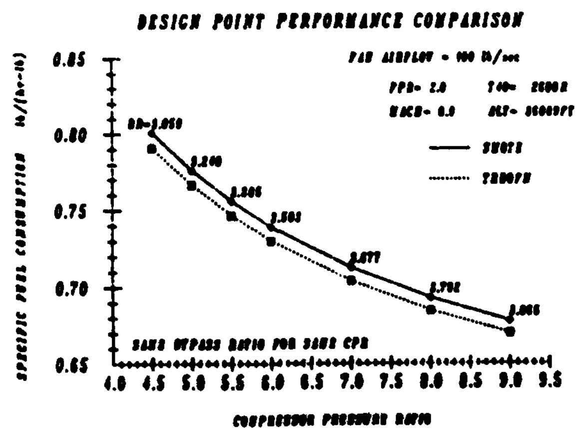

DESIGN POINT PERFORMANCE COMPARISON
4900
4800
4700
4600
4500
4400
4300
4200
NET THRUST (lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

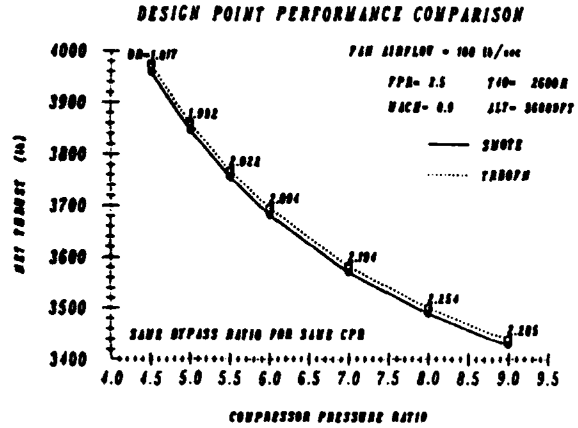

DESIGN POINT PERFORMANCE COMPARISON
0.90
0.85
0.80
0.75
0.70
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
SAME BYPASS RATIO FOR SAME CPR
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5
COMPRESSOR PRESSURE RATIO

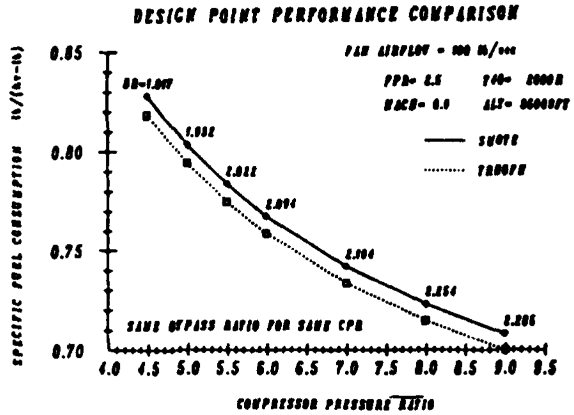

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

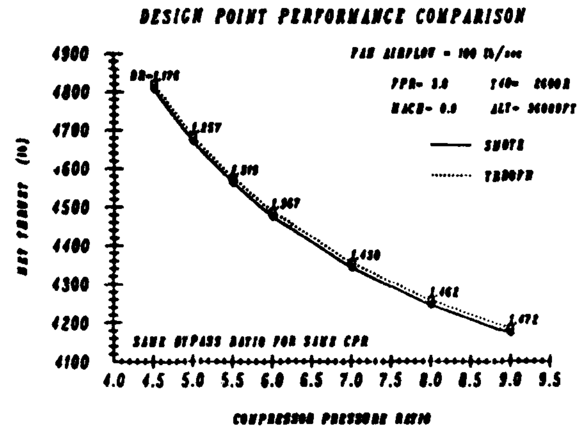

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

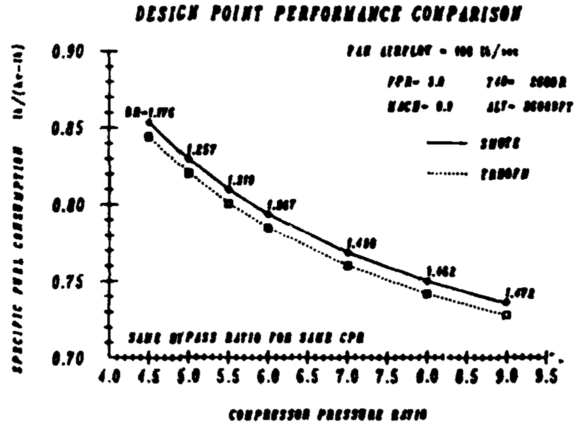

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

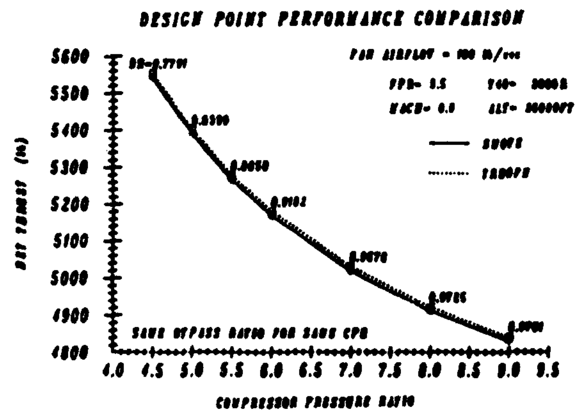

DESIGN POINT PERFORMANCE COMPARISON
SAME BYPASS RATIO FOR SAME CPR
COMPRESSOR PRESSURE RATIO

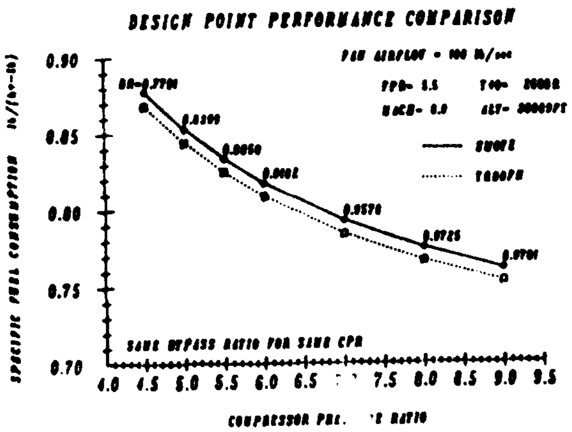

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
4000
3900
3800
3700
3600
3500
3400
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

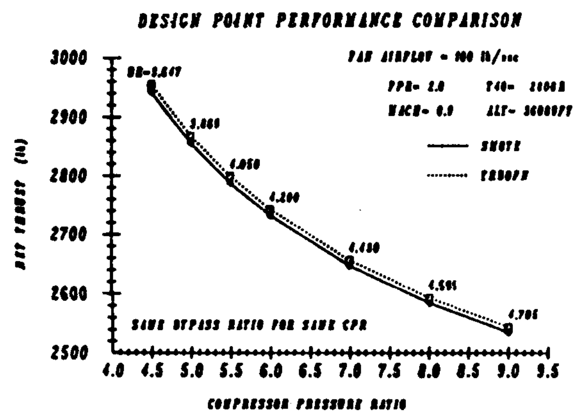

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
0.85
0.80
0.75
0.70
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

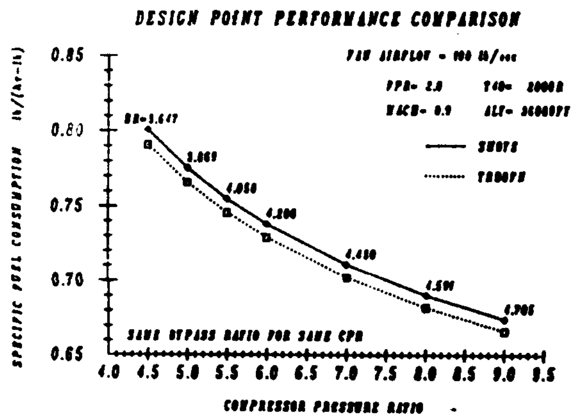

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
4900
4800
4700
4600
4500
4400
4300
4200
4100
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

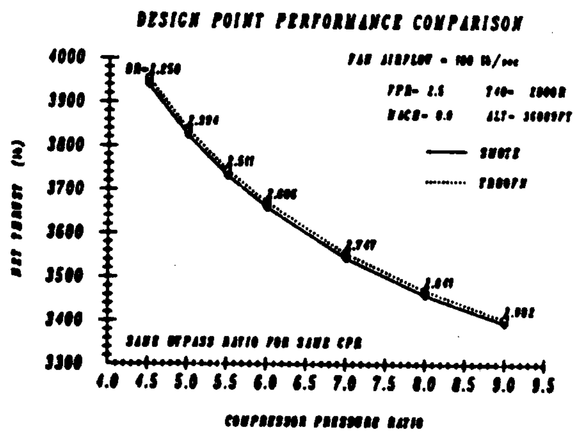

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
0.90
0.85
0.80
0.75
0.70
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

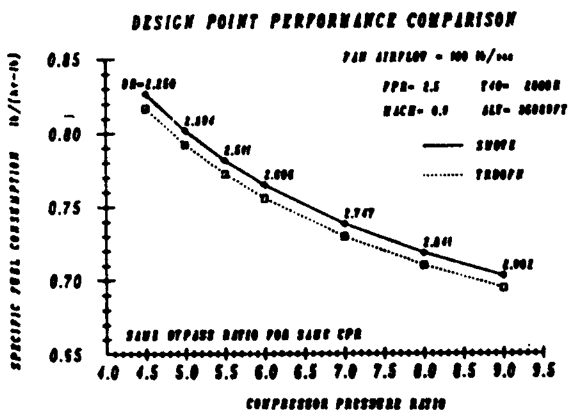

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
5600
5500
5400
5300
5200
5100
5000
4900
4800
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

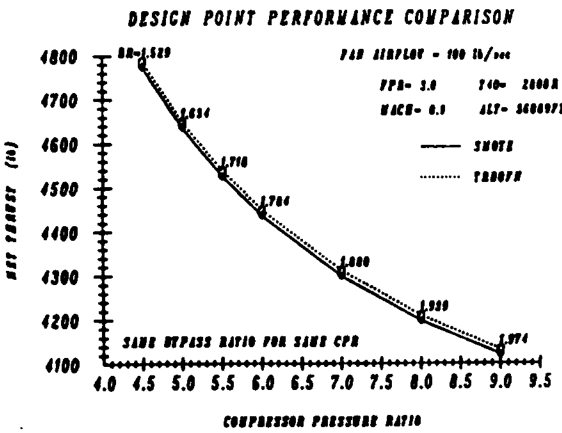

DESIGN POINT PERFORMANCE COMPARISON
FAN AIRFLOW = 100 lb/sec
SHOTE
TBBOFN
SAME BYPASS RATIO FOR SAME CPR
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
0.90
0.85
0.80
0.75
0.70

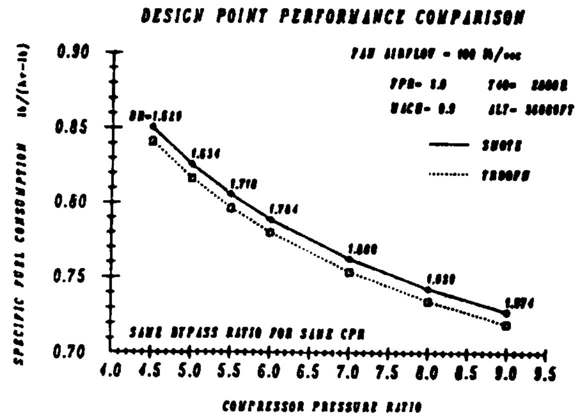

DESIGN POINT PERFORMANCE COMPARISON
3000
2900
2800
2700
2600
2500
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

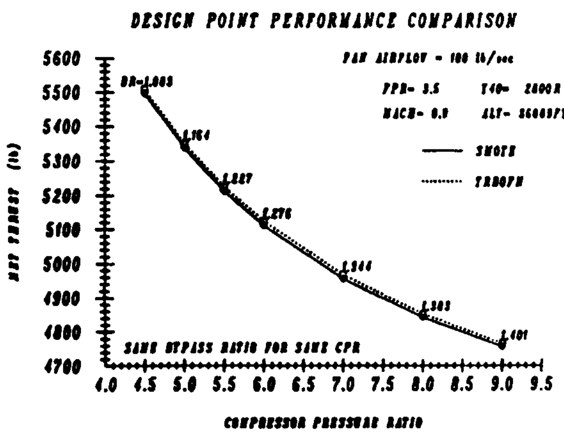

DESIGN POINT PERFORMANCE COMPARISON
0.85
0.75
0.70
0.65
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5

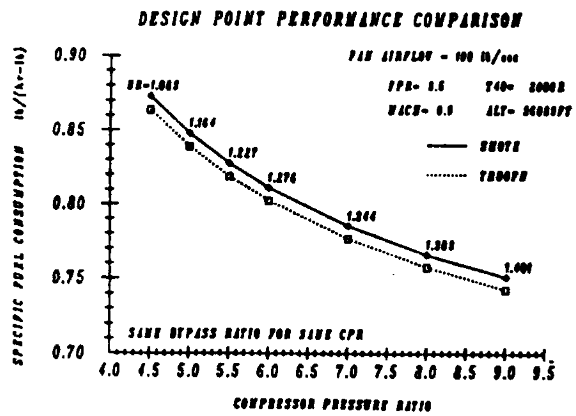

DESIGN POINT PERFORMANCE COMPARISON
4000
3700
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5


DESIGN POINT PERFORMANCE COMPARISON
0.85
0.80
0.75
0.70
4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0 9.5


DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SHOTE
TRBOFN


DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SHOTE
TRBOFN

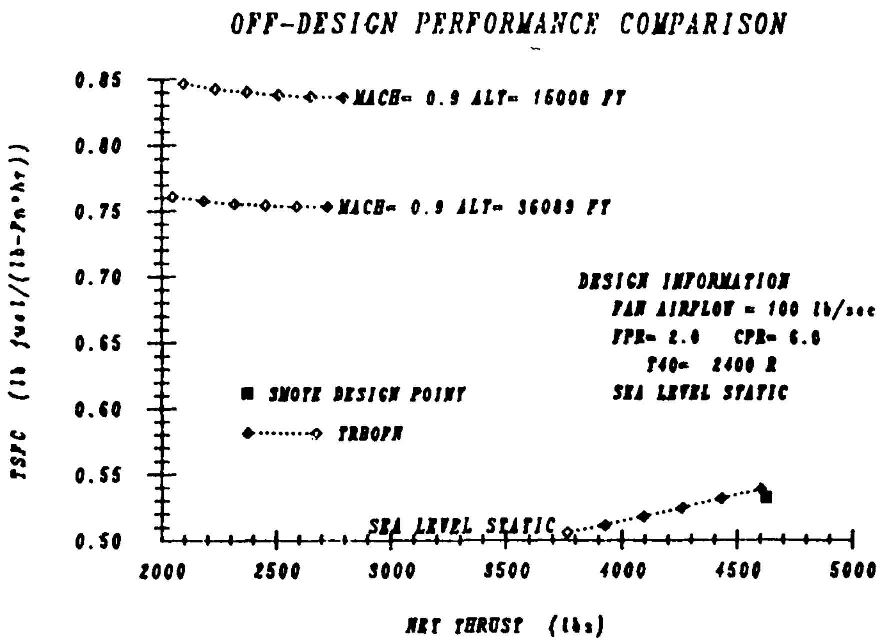

DESIGN POINT PERFORMANCE COMPARISON
NET THRUST (lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SHOTE
TRBOFN

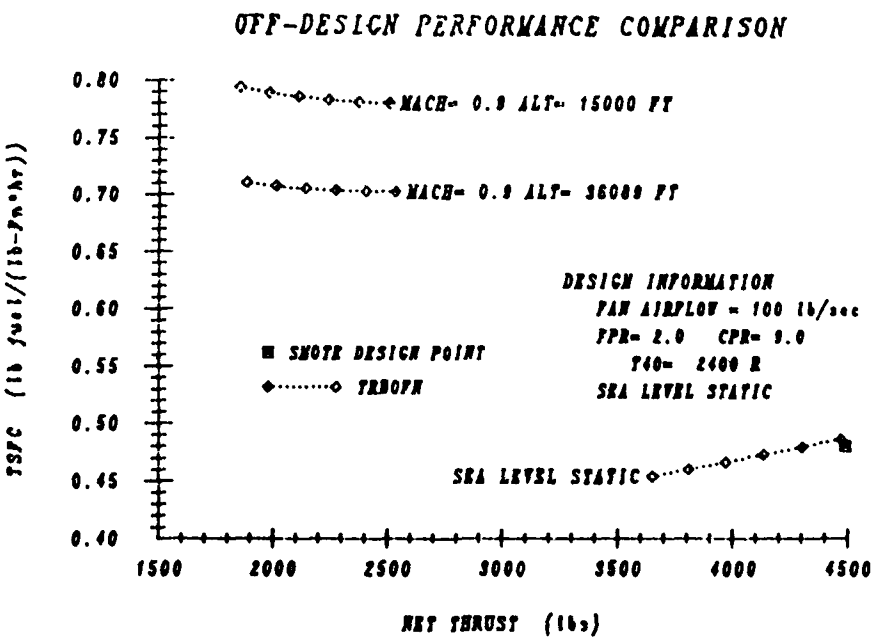

DESIGN POINT PERFORMANCE COMPARISON
SPECIFIC FUEL CONSUMPTION lb/(hr-lb)
COMPRESSOR PRESSURE RATIO
SAME BYPASS RATIO FOR SAME CPR
SHOTE
TRBOFN

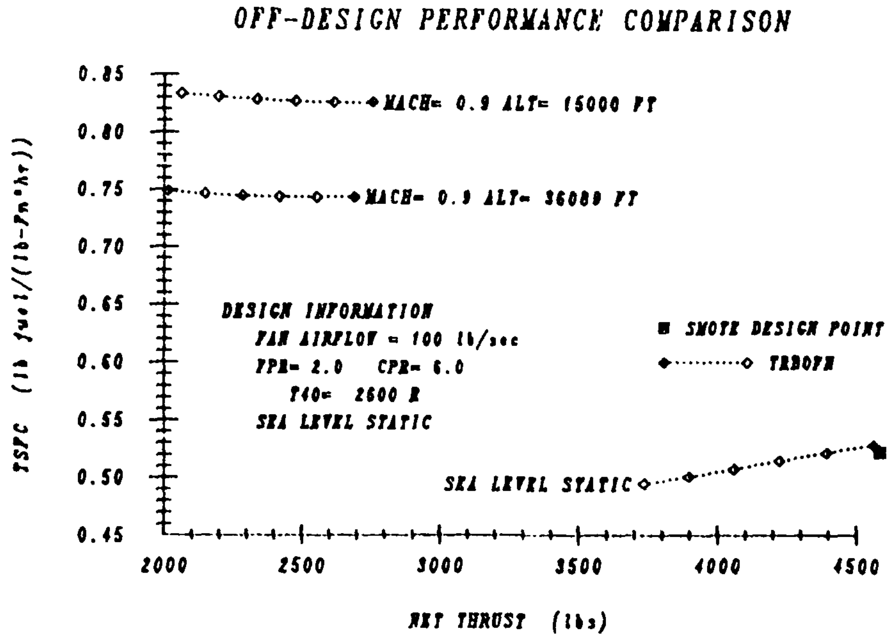
Off-Design Performance Comparison

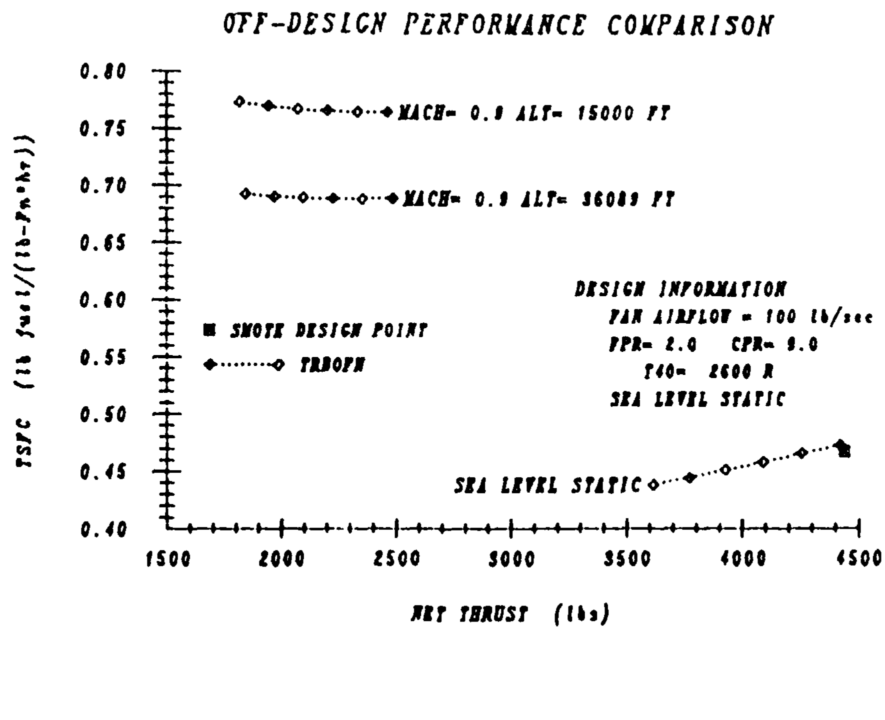
This section of the Appendix was intended to show how the throttled and off-design flight condition performance calculated by TRBOFN compares to that calculated by SMOTE. We wanted to show the comparison between net thrust and thrust specific fuel consumption (TSFC) at several off-design power points for each of several mixed flow turbofan engines. We encountered an insurmountable problem in undertaking this task. We could not get SMOTE to converge at any of the off-design power points we tried to run. SMOTE would only converge on design. The engines we tried to run were simplest case mixed flow turbofans in that they included no provisions for turbine cooling or overboard bleeds and after two months of trying, we could not get SMOTE to converge at even one of the off-design points we tried to run.

Because of the complications we encountered, each graph in this section shows thrust versus TSFC throttling information for each of three flight conditions calculated by TRBOFN (the design flight condition and two off-design flight conditions) but only the design point as calculated by SMOTE. The designs run include the same three turbine inlet temperatures (T40) as run in the design point comparison: 2400 R, 2600 R, and 2800 R. Two compressor pressure ratios were used in the designs: 6.0 and 9.0. Four different design flight conditions are included in this section: sea level static, Mach 0.7 at 15,000 ft altitude, Mach 0.9 at 15,000 ft, and Mach 0.9 at the tropopause, 36,089 ft.

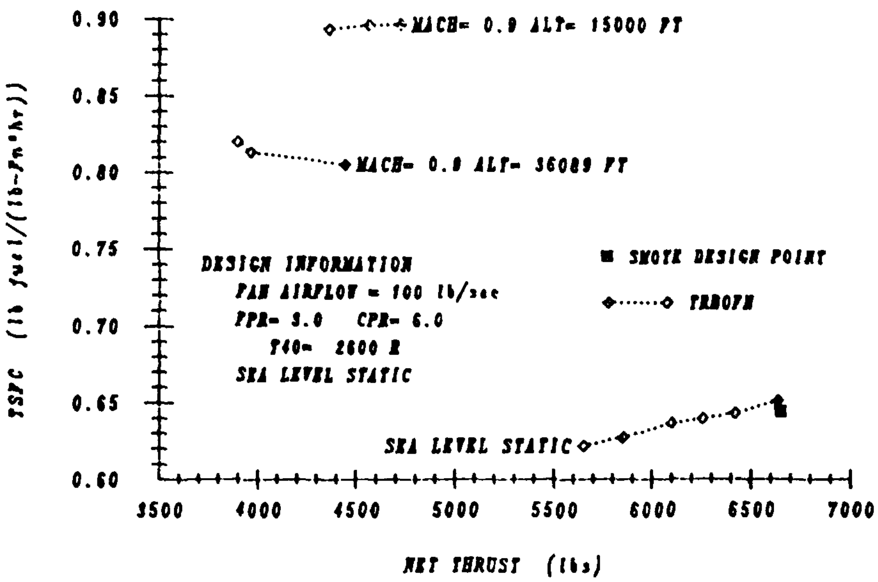

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 6.0
T40= 2400 R
SEA LEVEL STATIC
SNOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)

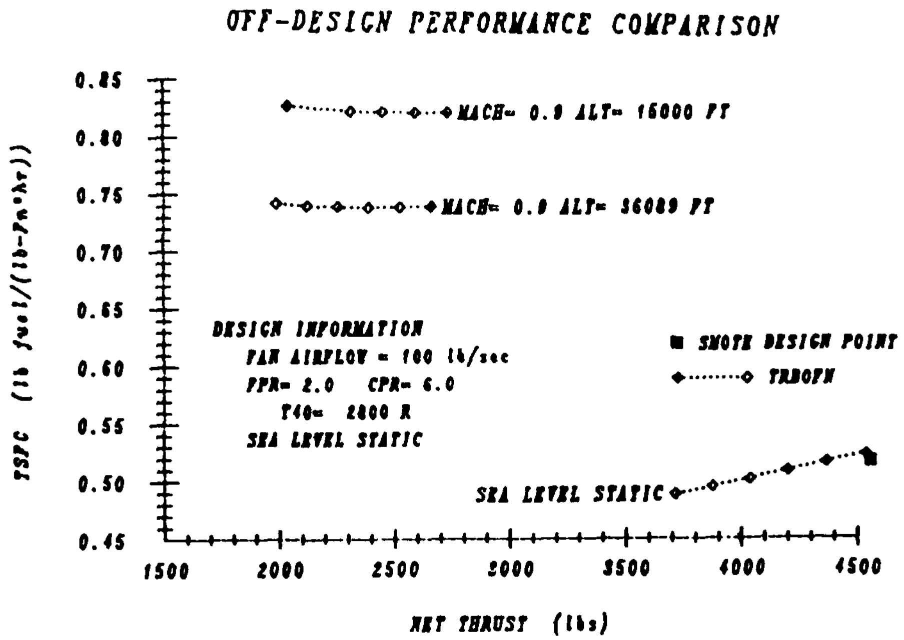

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 9.0
T40= 2400 R
SEA LEVEL STATIC
SNOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)

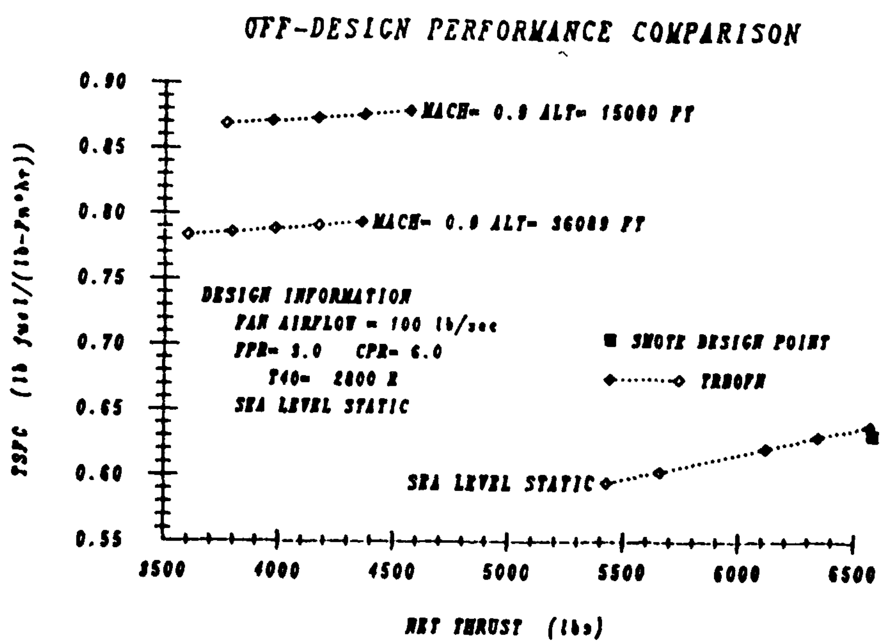

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 6.0
T40= 2600 R
SEA LEVEL STATIC
SMOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)


OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 9.0
T40= 2600 R
SEA LEVEL STATIC
SMOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)

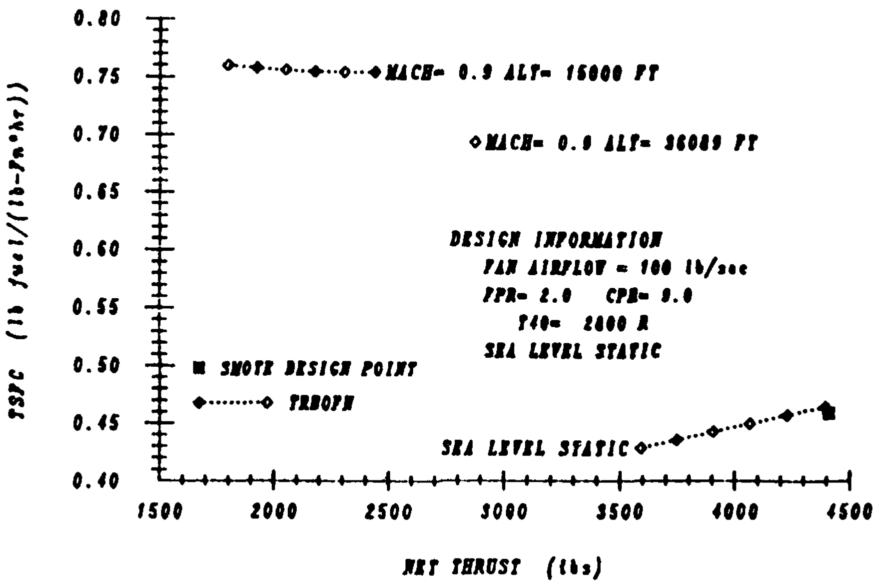
OFF-DESIGN PERFORMANCE COMPARISON



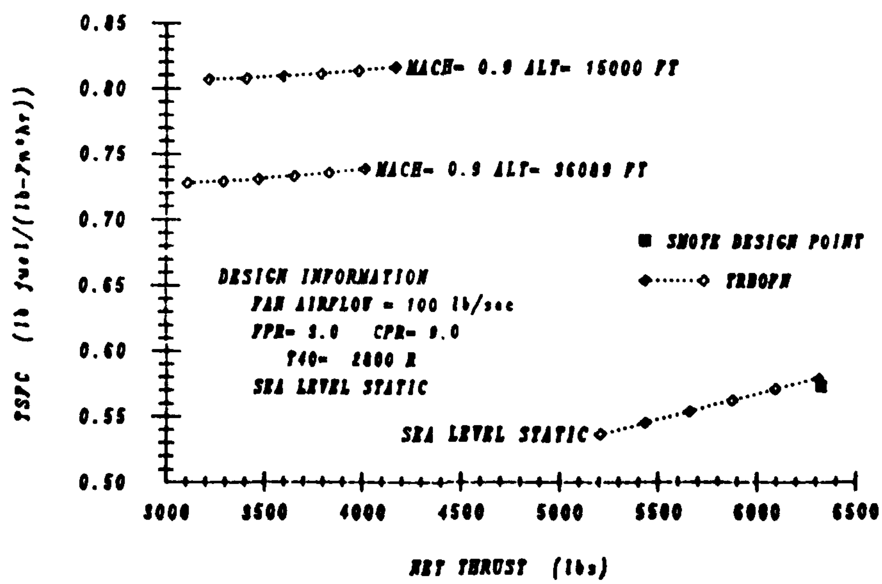

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.8 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 6.0
T40= 2800 R
SEA LEVEL STATIC
SNOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)


OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.8 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 CPR= 6.0
T40= 2800 R
SEA LEVEL STATIC
SNOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)

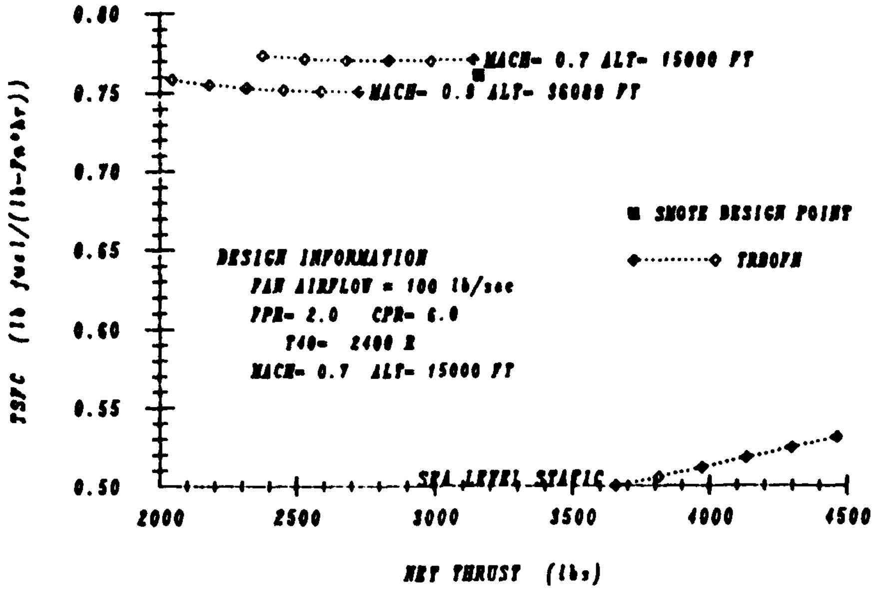
OFF-DESIGN PERFORMANCE COMPARISON



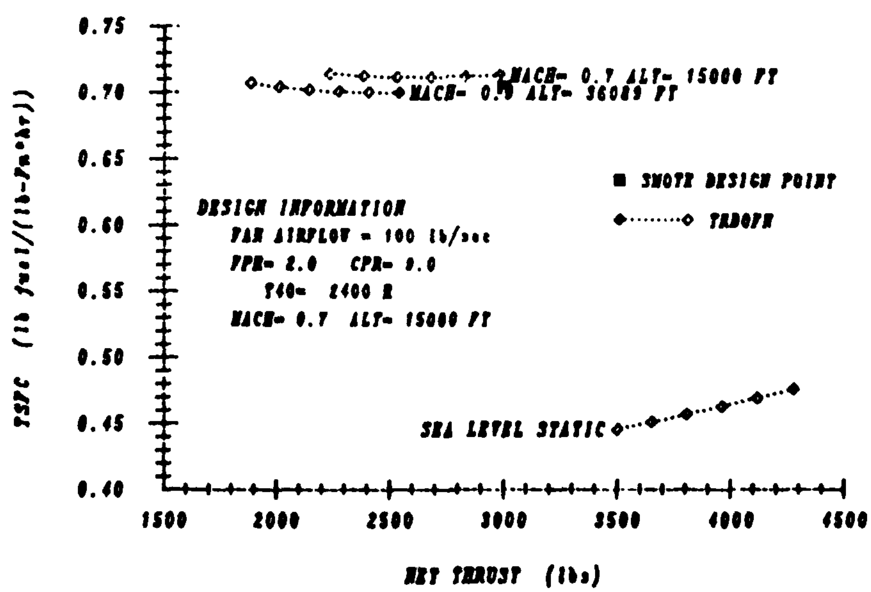
OFF-DESIGN PERFORMANCE COMPARISON

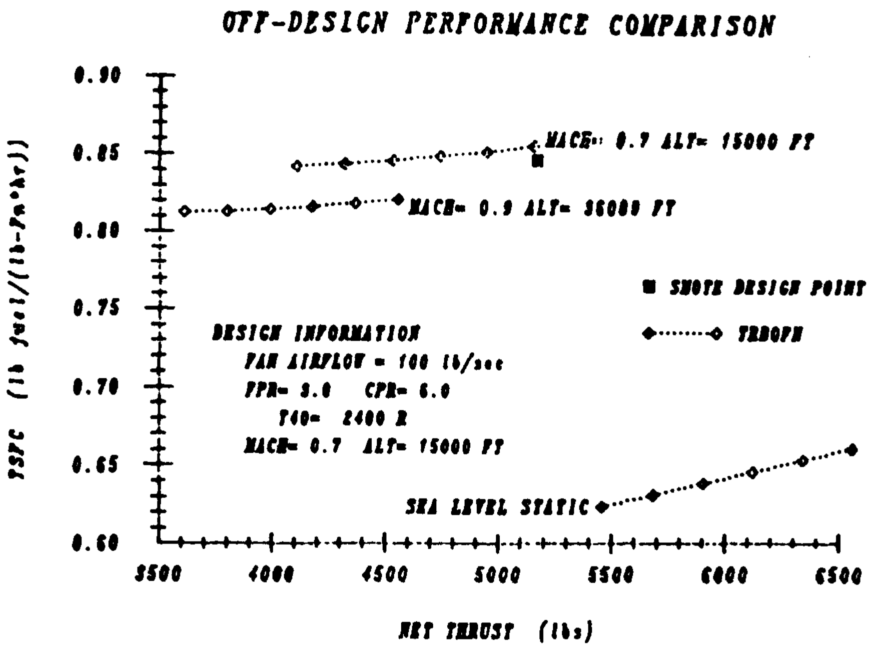


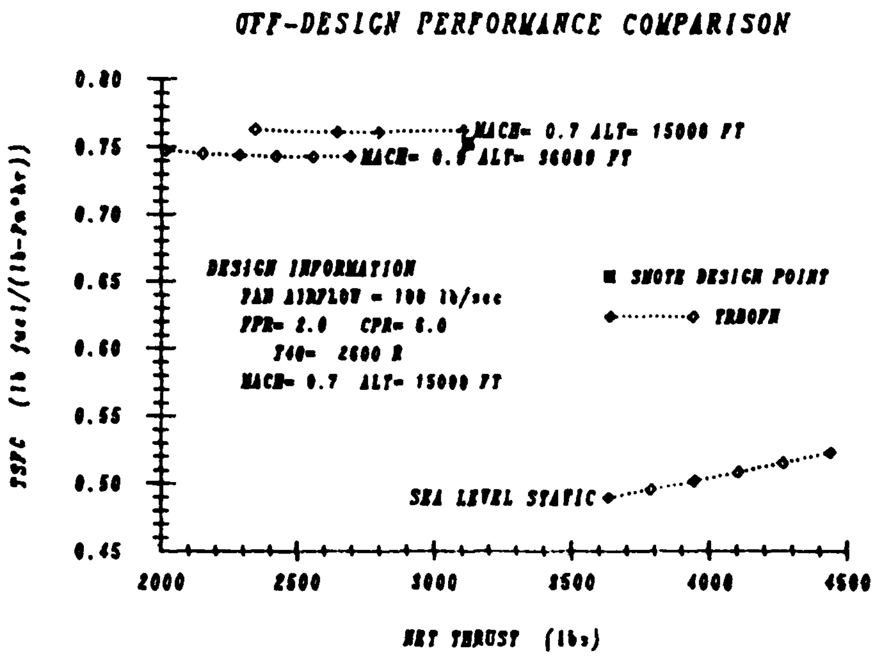
OFF-DESIGN PERFORMANCE COMPARISON

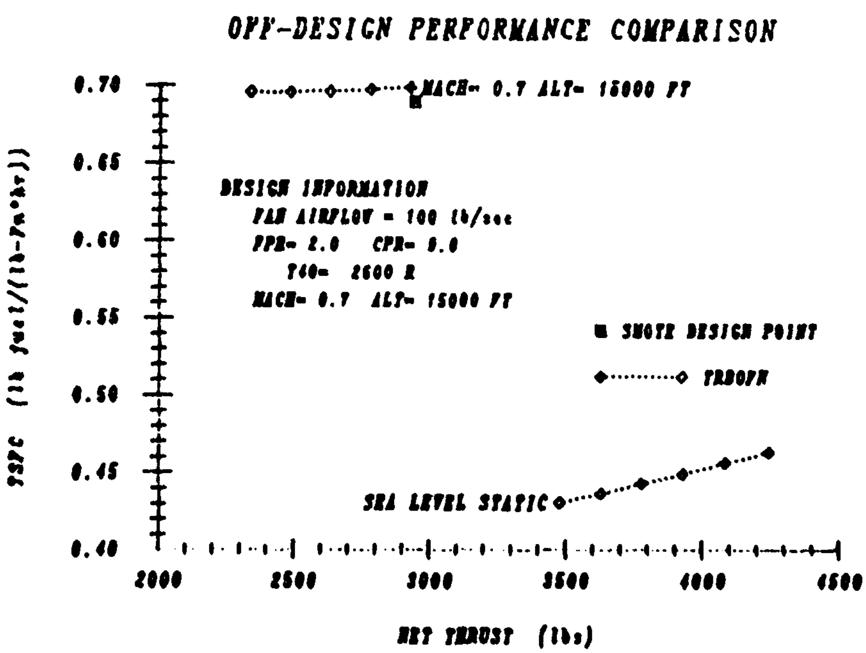


OFF-DESIGN PERFORMANCE COMPARISON

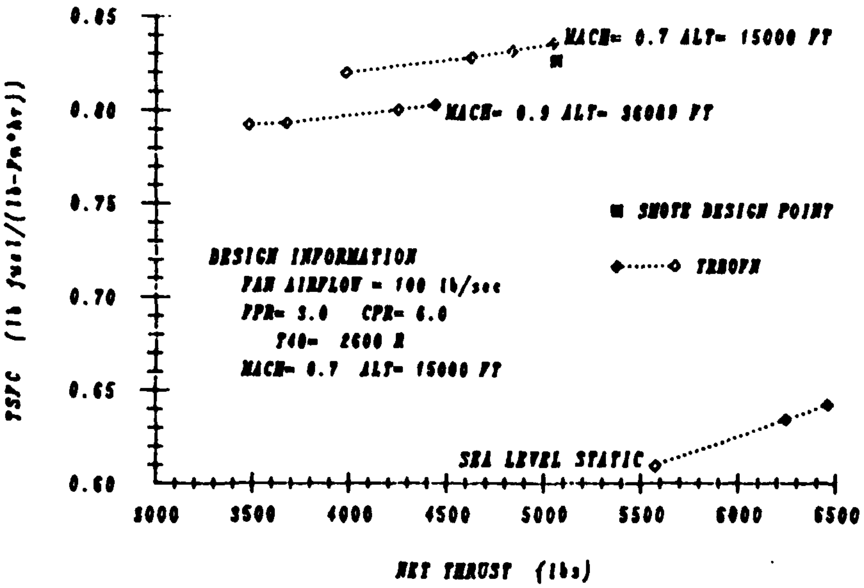



OFF-DESIGN PERFORMANCE COMPARISON
0.90
0.85
0.80
0.75
0.70
0.65
0.60
TSFC (lb fuel/(lb-Fn*hr))
MACH= 0.7 ALT= 15000 FT
MACH= 0.9 ALT= 36000 FT
SNOTE DESIGN POINT
TEDOFE
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 CPR= 6.0
T40= 2400 R
MACH= 0.7 ALT= 15000 FT
SEA LEVEL STATIC
3500
4000
4500
5000
5500
6000
6500
NET THRUST (lbs)

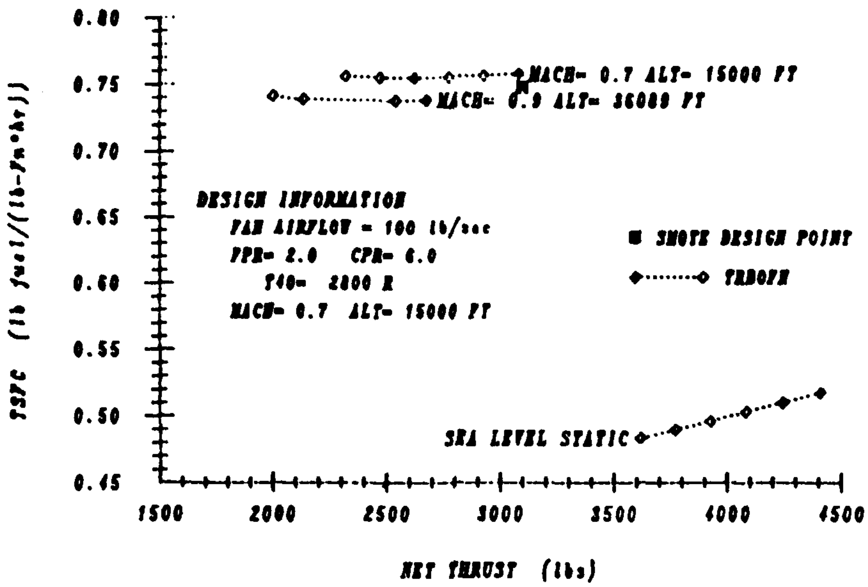

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.7 ALT= 15000 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 8.0
T40= 2600 R
MACH= 0.7 ALT= 15000 FT
SHOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
2000
2500
3000
3500
4000
4500


OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.7 ALT= 15000 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 8.0
T40= 2600 R
MACH= 0.7 ALT= 15000 FT
SHOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)
0.70
0.65
0.60
0.55
0.50
0.45
0.40
2000
2500
3000
3500
4000
4500

OFF-DESIGN PERFORMANCE COMPARISON



OFF-DESIGN PERFORMANCE COMPARISON



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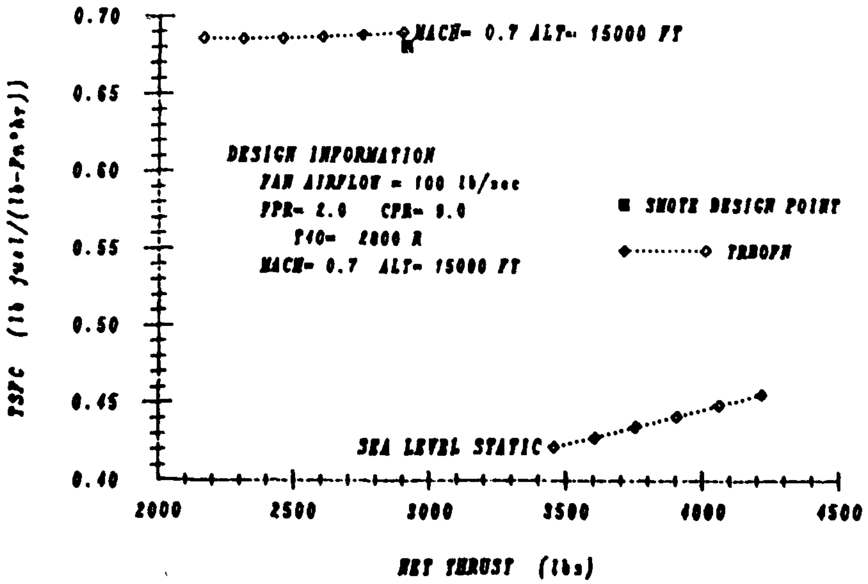

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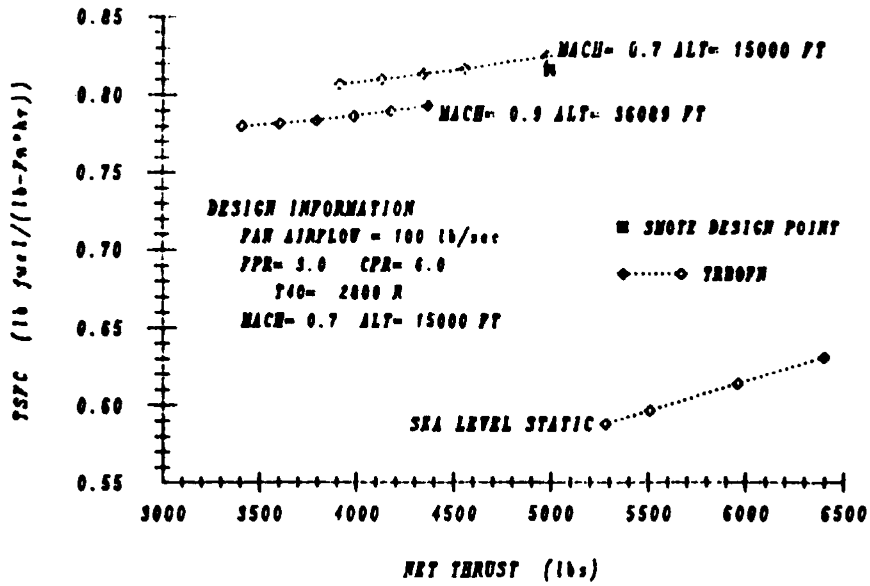

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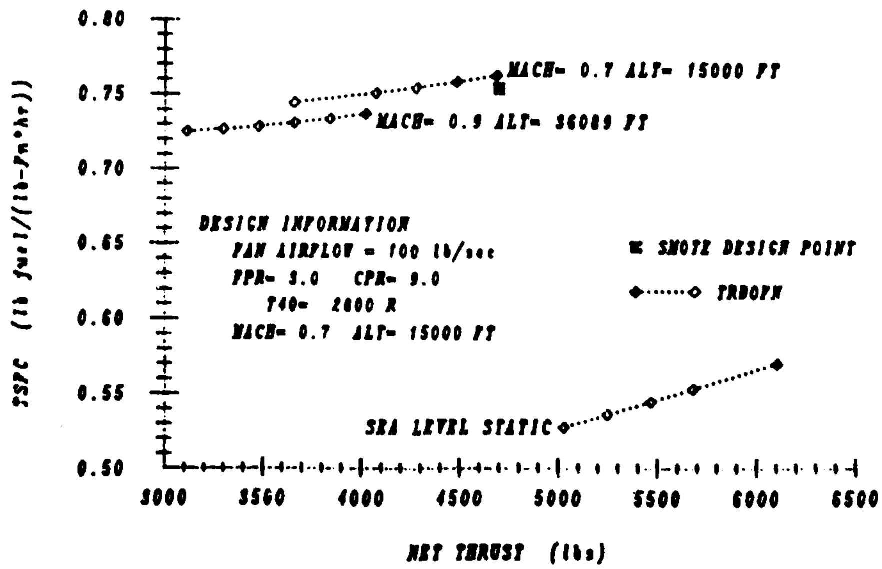
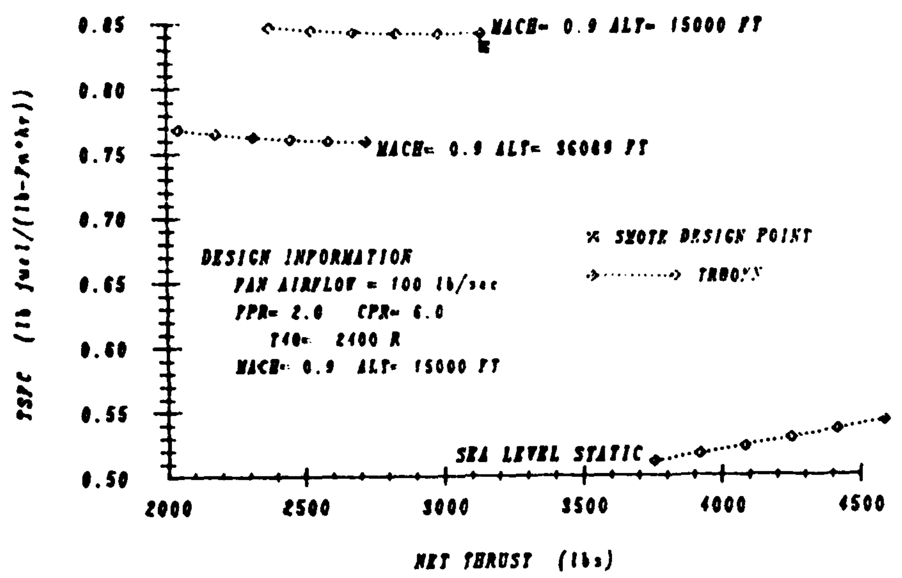
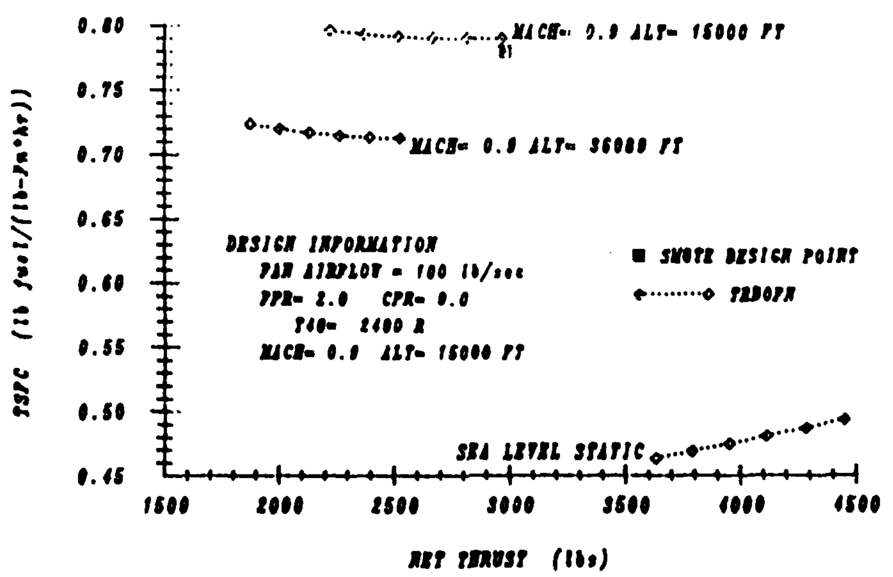
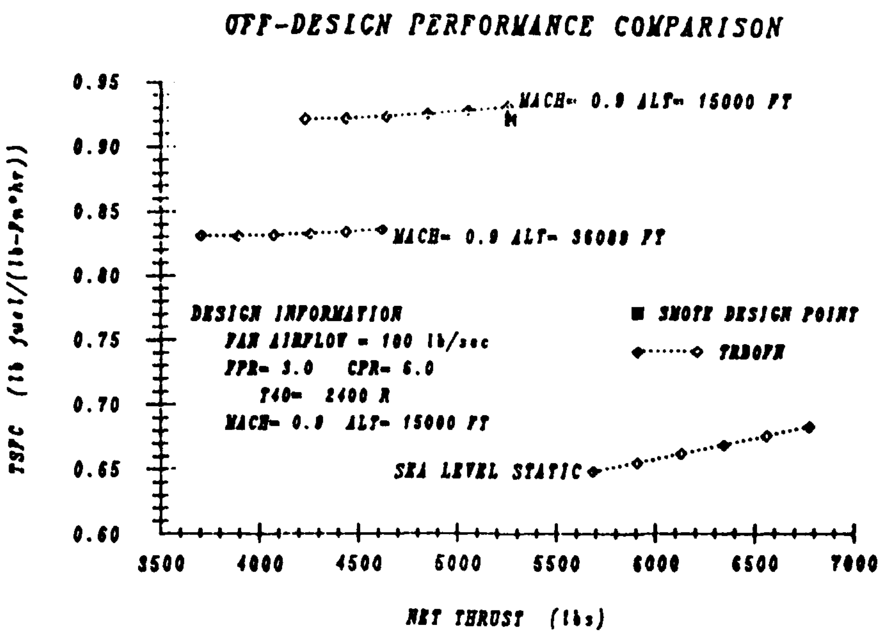


OFF-DESIGN PERFORMANCE COMPARISON

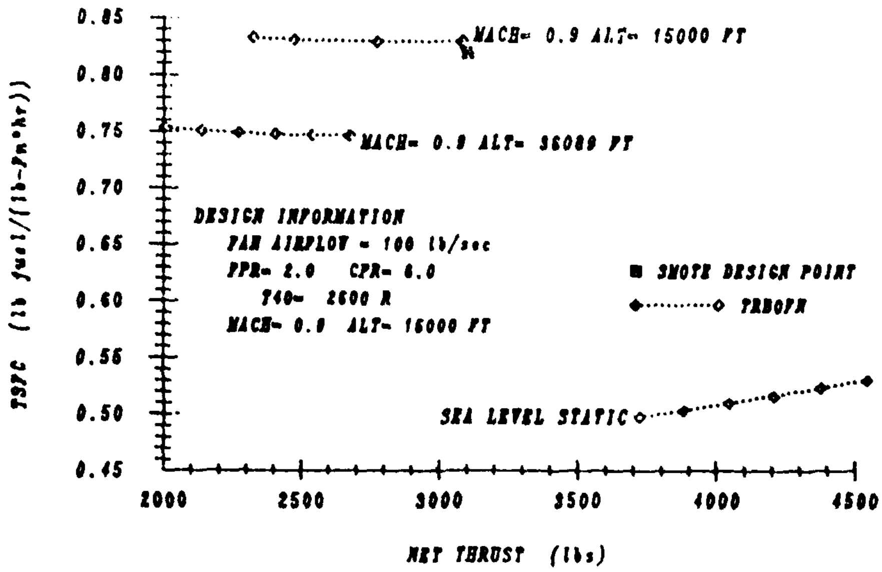


OFF-DESIGN PERFORMANCE COMPARISON

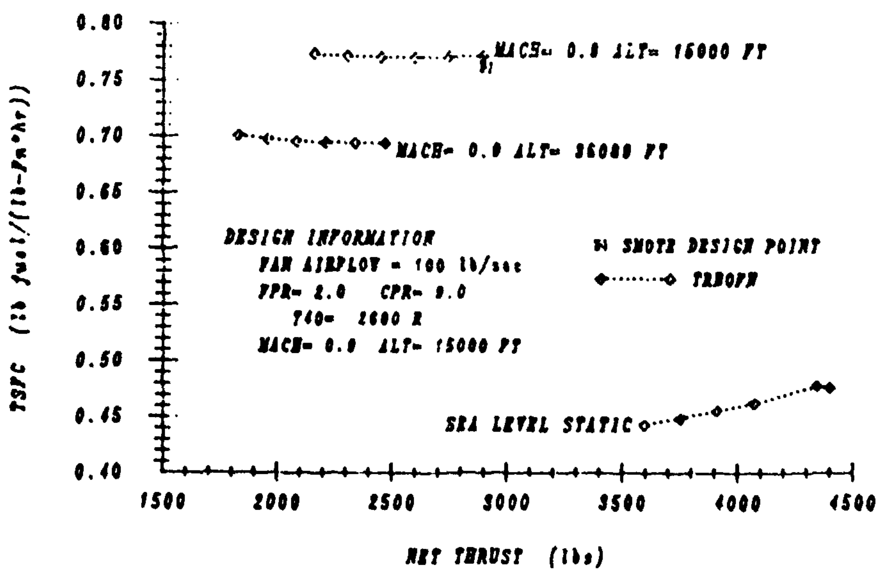


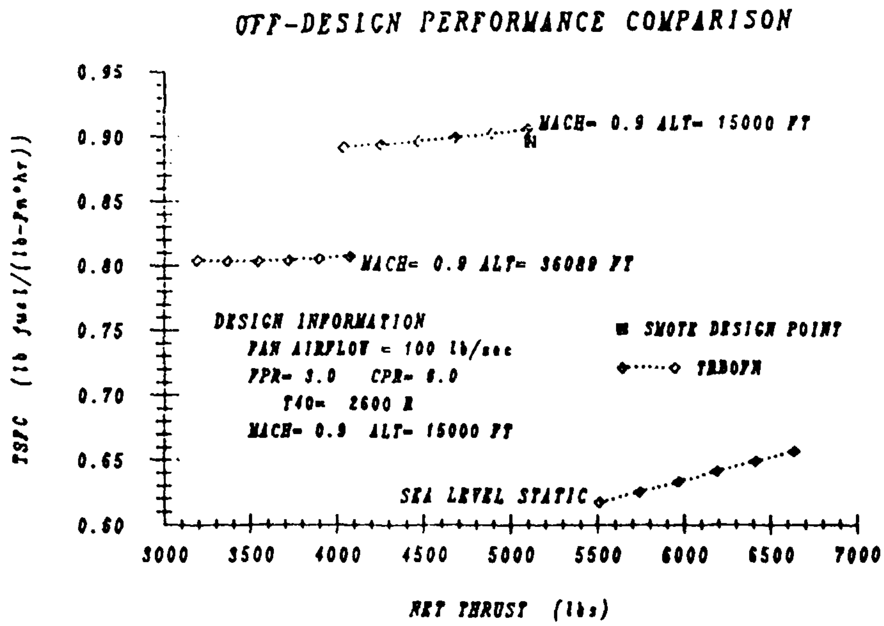

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 CPR= 6.0
T40= 2400 R
MACH= 0.9 ALT= 15000 FT
SNOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
3500
4000
4500
5000
5500
6000
6500
7000

OFF-DESIGN PERFORMANCE COMPARISON

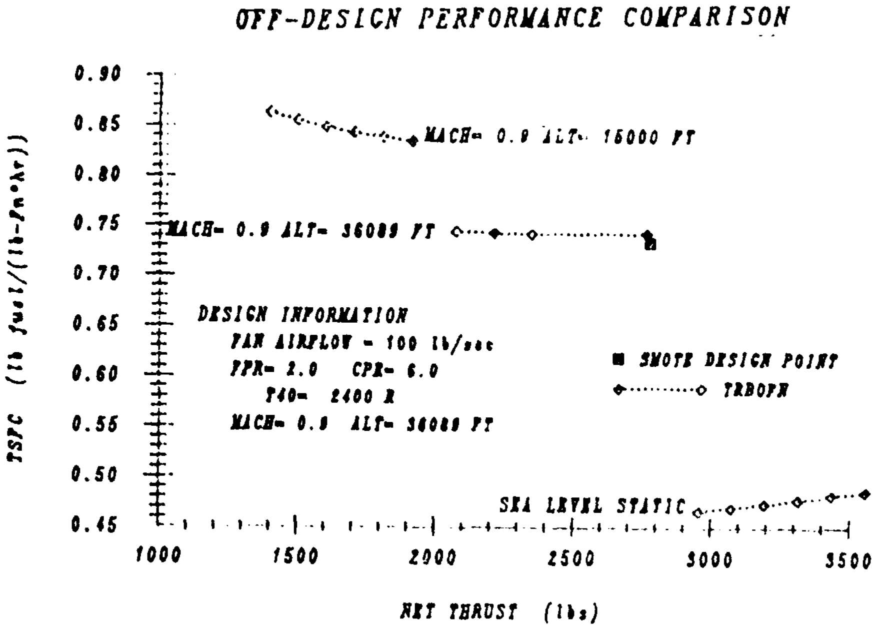


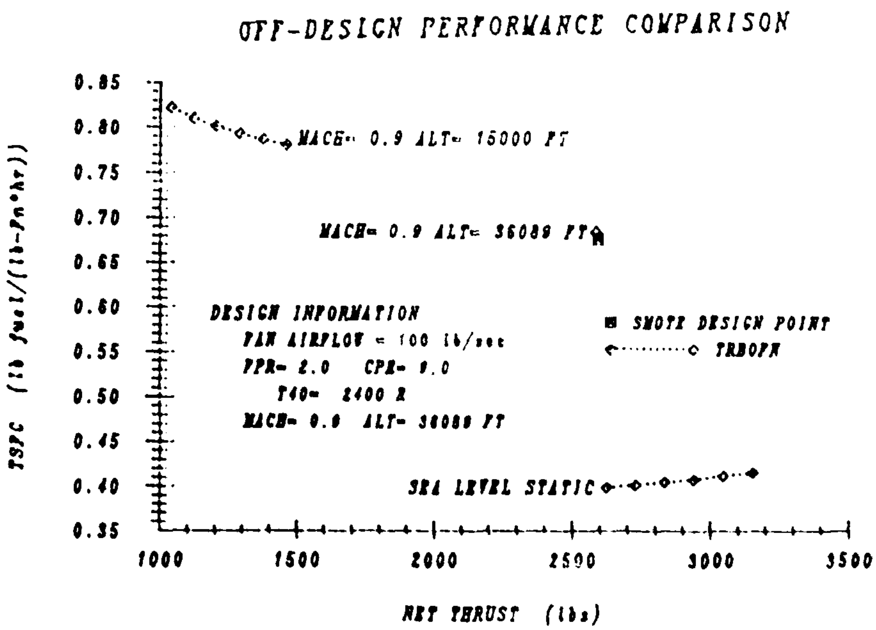
OFF-DESIGN PERFORMANCE COMPARISON



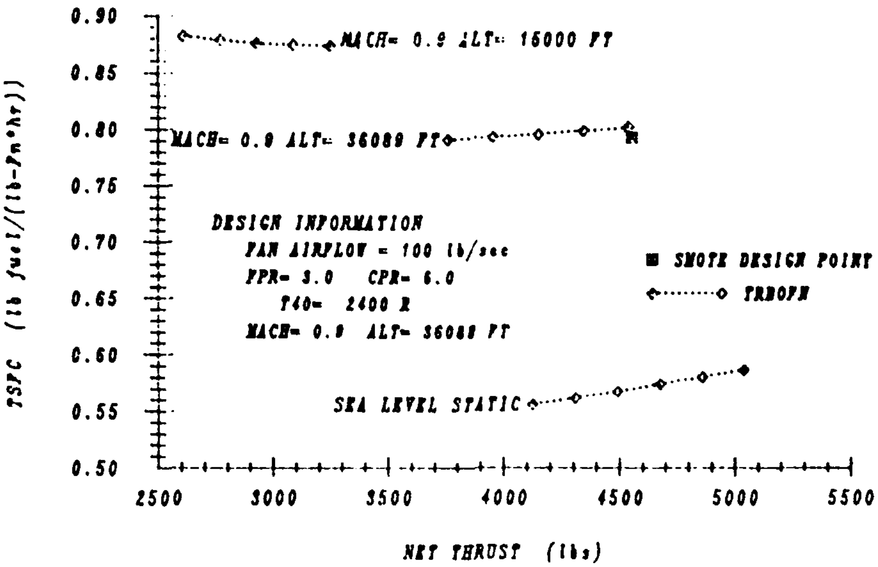


OFF-DESIGN PERFORMANCE COMPARISON
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
TSFC (lb fuel/(lb-Fn*hr))
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 3.0 CPR= 8.0
T40= 2600 R
MACH= 0.9 ALT= 15000 FT
SMOTE DESIGN POINT
TBBOFN
SEA LEVEL STATIC
3000
3500
4000
4500
5000
5500
6000
6500
7000
NET THRUST (lbs)

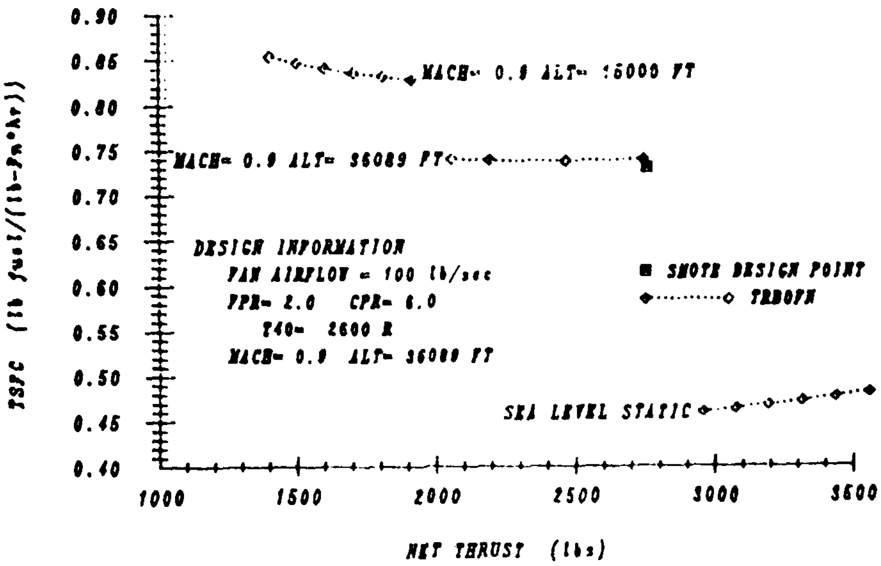

OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 6.0
T40= 2400 R
MACH= 0.9 ALT= 36089 FT
SMOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)


OFF-DESIGN PERFORMANCE COMPARISON
MACH= 0.9 ALT= 15000 FT
MACH= 0.9 ALT= 36089 FT
DESIGN INFORMATION
FAN AIRFLOW = 100 lb/sec
FPR= 2.0 CPR= 9.0
T40= 2400 R
MACH= 0.9 ALT= 36089 FT
SMOTE DESIGN POINT
TRBOFN
SEA LEVEL STATIC
TSFC (lb fuel/(lb-Fn*hr))
NET THRUST (lbs)

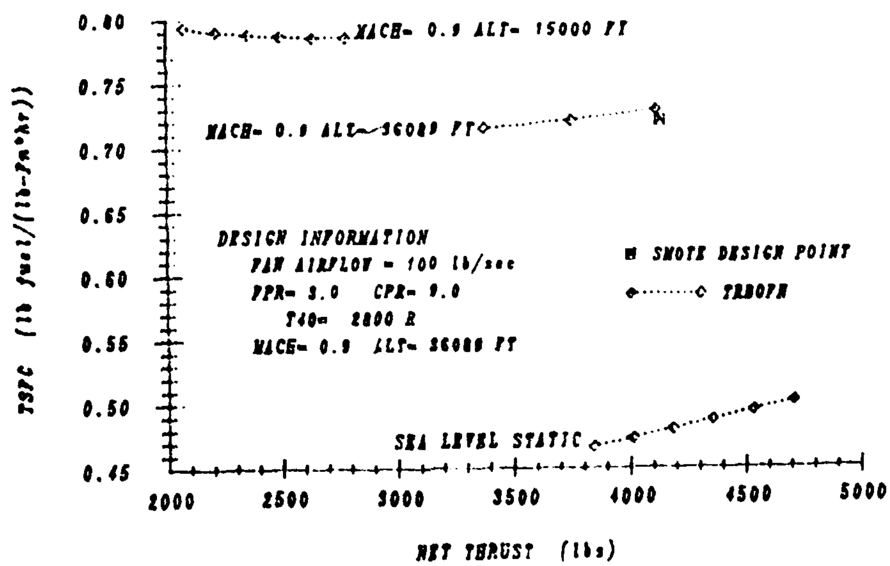
OFF-DESIGN PERFORMANCE COMPARISON



OFF-DESIGN PERFORMANCE COMPARISON



OFF-DESIGN PERFORMANCE COMPARISON



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